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Review Article

Interplanetary Magnetic Fields and the Propagation of Cosmic Rays*

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Abstract. Results and limitations of the diffusion-convection model for cosmic-ray propagation in the interplanetary space are presented. We first discuss magnetic field fluctuations on various scales, in particular the power spectral representation and its relation to cosmic ray diffusion in pitch angle and real space, and the non-resonant scattering at magnetic field discontinuities. The large variation of the fluctuation level with heliocentric longitude is partly ordered by the high-speed solar wind streams.

In the second part we analyze how far the diffusion model can carry us to obtain a unified view for the propagation of both galactic and solar cosmic rays. It is shown that mean free paths derived from time-intensity profiles of solar events increase when solar injection processes are taken into account. We derive a picture in which the local mean free path is on the average relatively large (of the order 0.1 AU for rigidities below a few hundred MV). The propagation conditions are highly variable, ranging from locally almost convective transport to scatter-free propagation.

The long term variations are much less pronounced. It seems as if the local propagation conditions do not reflect the 11 year modulation of galactic cosmic rays, apart from the several GeV energy range.

In the final section we mention some of the limitations of the diffusion model and discuss in particular the concept of collimated convection. It is stressed that we require detailed knowledge of the type of magnetic field fluctuations, of the pitch-angle scattering process, and of a theory delivering accurate predictions of the cosmic-ray transport coefficients from measured interplanetary magnetic field properties.

Key words: Coronal Propagation — Diffusion — Anisotropies — Alfvén-Waves — Discontinuities — Modulation — High-Speed Streams — Power Spectra — Radial Gradients — Resonance Interaction.

1. Introduction

The concept of cosmic ray scattering by magnetic field irregularities was invoked very early in connection with the observed isotropy of cosmic ray incidence and the necessary long storage times in the galaxy (e.g.

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* Dedicated to Professor Georg Pfotzer with best wishes for his 65th anniversary.

Unsöld, 1951; Morrison *et al.*, 1954). The transfer of this model to the propagation of cosmic rays in interplanetary space was initiated by transient phenomena of solar origin: the time-intensity profile of the solar proton event of 23 February 1956 was explained by a diffusion model by Meyer *et al.* (1956), and Morrison (1956) developed a model for Forbush-decreases, based on diffusion of particles into disordered plasma clouds.

In the early diffusion models, cosmic ray scattering was thought to take place at isolated "scattering centers". In the diffusion-convection model by Parker (1958) the isolated plasma clouds emitted during solar flares were replaced by the continuous solar wind carrying frozen-in magnetic field irregularities. The random walk of cosmic-ray particles is caused by at least two effects: the particle pitch angle changes continuously as a consequence of interactions with the small fluctuations; in addition, a few large angle scatterings or even reflections may occur at some of the large kinks in the field.

The diffusion model became more and more successful to describe and order a large amount of cosmic-ray data, and finally it appeared to become possible to relate the essential model parameter, the scattering mean free path $\lambda_{\parallel}$ along the average field, to observed interplanetary magnetic field properties by treating the resonant interaction of charged particles with random magnetic fields (Jokipii, 1966). As early as 1966 Jokipii expressed the hope that "*applications of the formalism to direct observations of the interplanetary magnetic field should make possible a quantitative discussion of cosmic-ray propagation and modulation in the solar system*".

The years from 1966 to 1972 were characterized by the following developments:

1. Derivation of cosmic-ray scattering *mean free paths* from measured interplanetary magnetic field (IMF) spectra by making use of the resonance-scattering formalism (see Jokipii, 1971, for a general discussion).
2. Formulation of the full *transport equation* for the cosmic-ray density and streaming: diffusion-convection models with anisotropic diffusion and inclusion of adiabatic energy losses in the solar wind (see Jokipii and Parker, 1970).
3. Fits of time-intensity profiles of *solar particle events* to solutions of (2) (see Axford, 1972).
4. Fits of spherically symmetric steady-state solutions of (2) to the *11 year modulation* of galactic cosmic rays (see Gleeson, 1973).
5. If one tries to combine the results of (3) and (4), it should be possible to describe the propagation medium on the average by a certain *radial dependence* of the mean free path. By using (1), this variation can be predicted if the radial variation of IMF fluctuations is treated theoretically. This has been done for one special case: the scattering of cosmic rays due to Alfvén waves (see Völk *et al.*, 1974).

For some time it appeared then that the large amount of experimental and theoretical work summarized very briefly under (1) to (5) above by quoting some representative work would culminate in a unified view of cosmic-ray propagation in interplanetary space: A cosmic-ray particle of rigidity P which stays momentarily at a distance r from the Sun, propagates back and forth along the interplanetary magnetic field with a mean free path $\lambda_{\parallel}(r, P)$. This mean free path can be obtained by local properties of the interplanetary magnetic field at the same position r. Solutions of the transport equations in a spherically symmetric medium or along a field line bundle are uniquely determined by the boundary conditions once the radial dependences of $\lambda_{\parallel}(r, P)$ and the solar wind speed $V_w(r)$ are known. Short and long term variations in the observed cosmic-ray propagation properties should be related in a well defined manner to changes in the interplanetary plasma and magnetic field properties.

It has turned out during the last two or three years that it was too early for such an optimistic view. New evidence from theory and experiment came in the following fields:

(A) *In situ* measurements up to a distance of 5 AU from the Sun have led to modifications about the radial dependence of the mean free path.

(B) Deviations from spherical symmetry may be needed to explain certain features of galactic cosmic ray modulation.

(C) Solar transport and injection effects determine the time-intensity profiles of solar events to a large degree.

(D) Large magnetic field discontinuities were shown to play an important role in controlling cosmic ray density distributions in space.

(E) General sceptizism on the validity of the quasi-linear approach (1) arose and could be substantiated.

(F) Anisotropy measurements during solar cosmic ray events showed substantial deviations from the prediction of diffusion models.

Points A to D refer to modifications in the numerical values of the cosmic ray mean free path and its radial dependence and can still be treated within the framework of diffusion-convection models. Points E and F are of a fundamental nature and require new approaches to the theoretical treatment of the propagation problem. A paper by Fisk *et al.* (1974) closes by stating "*In conclusion, then, no complete theory appears to be available at this time accurately determing cosmic-ray diffusion coefficients from observed properties of the interplanetary magnetic field.*"

It is the purpose of this paper to summarize a few of the efforts and results which have made the diffusion model so appealing (section 3) and to continue by presenting some evidence for the limitations of the diffusion model (section 4). The discussion is preceded by a presentation of some features of the interplanetary magnetic field (section 2), in particular as far as they are important for cosmic ray propagation.

2. *Interplanetary Magnetic Field Structure*

Before starting let us keep in mind that solar and galactic cosmic ray observation studies span a range of Larmor radii of many orders of magnitude in a given magnetic field configuration and that it is necessary therefore to discuss the field structure on various scales. We shall follow the classification of scales introduced by Burlaga (1969a). The relation between time scales, spatial scales and cosmic ray particle energies is to be understood as follows: if the field is frozen into the plasma and transported across an observer with the solar wind speed V_w, then a spatial scale L_c in the field in the radial direction is seen as a temporal scale $T_c = L_c/V_w$. An energetic particle will have a Larmor radius of this size L_c, if its magnetic rigidity P_c is related to L_c by $P_c = B\,L_c$. Here B is the "average" field magnitude, which in general has a useful meaning, because B changes slowly within the scale L_c. When relating these three quantities one usually takes $V_w =$ 400 km/sec, $B = 5\gamma$. To give an example: $T_c = 1$ hour corresponds to $L_c = 1.4 \cdot 10^6$ km $\approx 10^{-2}$ AU, $P_c \approx 2.1$ GV (or kinetic energy 1.4 GeV for a proton).

Let us discuss the largest scales first. To get an impression how the IMF looks like on various time scales the reader is referred to Figs. 1—4 in Burlaga (1969a). Many more details than presented here can be found in extended reviews by Ness (1968), Schatten (1971), Burlaga (1971a, 1972).

The Macro-Scale (Spiral and Sector-Structure)

In a model of quiet solar wind expansion the plasma streams radially away from the sun with uniform speed in time and solar longitude, leading to the ideal Archimedean spiral configuration (see Parker, 1963). At 1 AU and for a 400 km/sec wind speed the ideal spiral is inclined about 45° to the solar radius vector. Experimentally the spiral structure shows up if the magnetic field is averaged over sufficiently long time; the momentary field direction shows large variability. On the time scale of days (corresponding to Larmor radii of protons about 100 GeV at 1 AU) the magnetic field is organized into magnetic sectors in which the field points alternately toward and away from the sun (Wilcox and Ness, 1965). The number of sectors per solar rotation changes with the solar cycle (see Wilcox and Colburn, 1970). According to Iucci and Storini (1973), the average length of one sector is 4.3 days in 1965, 8 days in 1968. They also find that this effect causes a change in the upper rigidity cutoff for the diurnal variation from ≈ 50 GV during 1965 to ≈ 150 GV during 1968, which might be one cause of the solar cycle change in the diurnal variation.

The radial variations of the IMF structure between 1.0 and 4.3 AU as obtained by Pioneer 10 observations have recently been summarized by Smith (1974). Fig. 1 shows histograms for the three hour averages of the

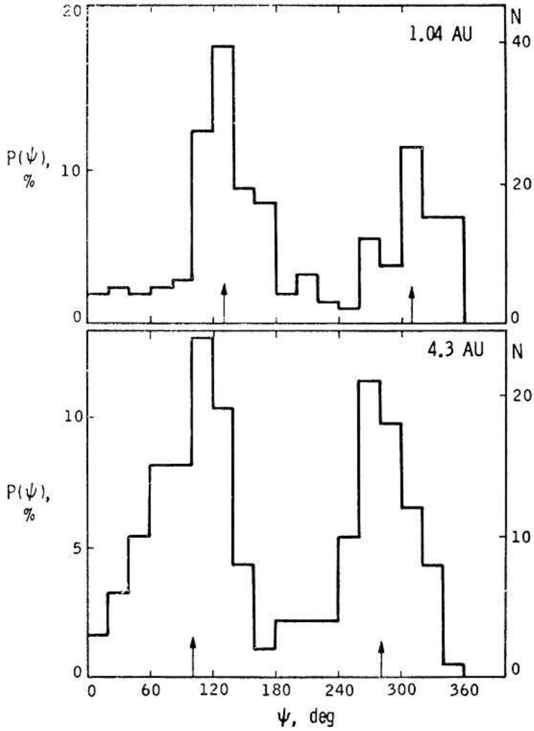

Fig. 1. Histograms of three hour averages of the spiral angle at 1.0 and 4.3 AU as obtained from the Pioneer 10 vector helium magnetometer. The vertical arrows at the bottom of each panel represent theoretical values for the smooth Archimedean spiral. (After Smith, 1974)

spiral angle ψ for the two heliocentric distances 1.04 and 4.3 AU. The organization of the IMF into toward sectors (left part of the histograms) and away sectors (right part) is clearly evident. The theoretically expected change in the spiral angle for a solar wind speed of 360 km/sec is from 309° at 1 AU to 281° at 4.3 AU and is indicated by the arrows at the bottom of the histograms. So the change in the average direction is consistent with the theoretical expectation of the Parker model; there is considerable spread around the average direction, but this is roughly the same at both locations.

We conclude therefore that on a large scale cosmic ray particles will find a well-ordered interplanetary magnetic field. Above 100 GV, the Larmor radius is sufficiently large for particles to "see" the sector structure, i.e. in general they do not stay within a sector of one polarity during one gyration. Consequences for particle trajectories are discussed by Barnden (1971). The curvature and gradients in the large scale IMF cause considerable

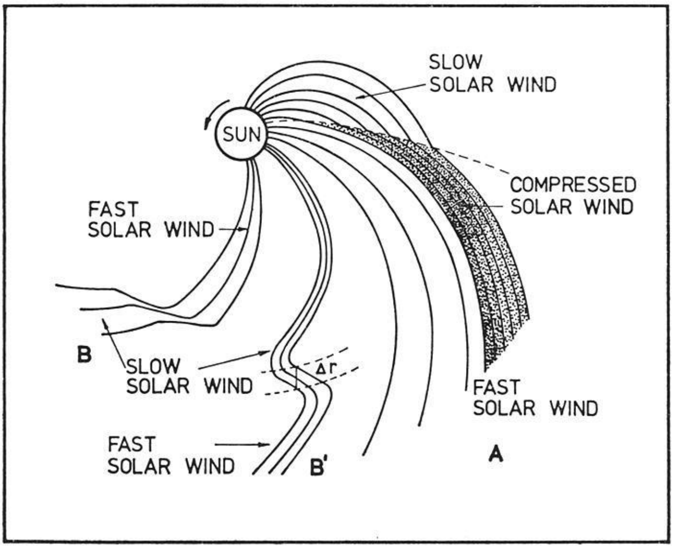

Fig. 2. Large scale interplanetary magnetic field structures (schematic) connected with non-uniform expansion of the solar wind. A: (Corotating) stream-stream interaction. B: Slow-fast sequence of solar wind emission from the same solar longitude. B′: Fast-slow sequence of solar wind emission from the same solar longitude

latitudinal drift of particles. Barnden and Bercovitch (1974, private communication) conclude that as a consequence galactic cosmic ray diffuse and drift to us through high latitude regions of the solar system instead of following the spiral field in the ecliptic plane, which gets more and more tightly wound up with increasing distance from the sun.

The Meso-Scale (Effects of Fast and Slow Solar Wind Streams)

The expansion of the solar wind can be non-uniform both in time and in solar longitude. In both cases the magnetic field lines will no longer coincide with the plasma stream lines in a corotating frame. In Fig. 2 we present schematically the expected magnetic field configuration for two simplified cases.

Case A corresponds to the stream-stream interaction: a high-speed stream overtakes the ambient slower solar wind due to the rotation of the sun. The structure of these "colliding streams" is extensively discussed e.g. by Hundhausen (1972). The resulting IMF configuration is somewhat exaggerated above (A) in Fig. 2. For a steady coronal source distribution this structure will corotate as a whole, and an observer in space will see an increase in plasma density and magnetic field magnitude before the fast solar wind arrives. The expected change in field direction is masked by the occurence of Alfvén waves, which are of particularly large amplitude at the leading edge of high-speed streams (Belcher and Davis, 1971).

In contrast to the stationary structure A, the *same* coronal region may emit solar wind with expansion speeds varying as a function of time. Observations have shown (Gosling, 1971; Gosling and Bame, 1972) that corotating structures normally do not persist for much longer than 2 or 3 days. Nolte and Roelof (1973b) have developed a method to construct the large-scale magnetic fields from solar wind speed measurements on several spacecrafts separated in heliographic longitude. They show the development of a double kink superimposed on the general spiral field (see Fig. 1 of their paper), if the solar wind speed is increased at the solar source over a finite range of longitudes for a finite time period. This structure propagates *radially* outward. The most disturbed part of the field line bundle may have an appearance as sketched under B in Fig. 2.

In the reverse situation, if the fast solar wind is followed by a slow solar wind from the same region, the direction of the field "kinks" is also reversed (see B′ in Fig. 2). An observer who sees the magnetic field carried along by the radially streaming plasma may now be connected with the *same* region on the sun for some time, in contrast to case A. Situation B′ is called a solar wind "dwell" (Roelof and Krimigis, 1973) and has important consequences for the discussion of long-lived solar particle events.

The large-scale bends in the field, which are traveling outwards, may act as partial barriers or reflectors for particles reaching regions of magnetic field compression. The finite extent and the variable location of such structures means that it depends on time and location of a flare whether solar particles traveling outwards will find this kind of obstacles for their propagation.

As a matter of fact directional changes occur on many different time scales. Belcher and Davis (1971) have analysed correlated changes in the components of the magnetic field and the plasma velocity and have identified aperiodic Alfvén waves occuring on time scales between 5 minutes and 4 hours, corresponding to wavelength of 0.03 AU and smaller. They are almost exclusively moving outward and therefore most probably of solar origin. One possible mechanism is the supergranular motion in the solar atmosphere and the resulting field-line random walk (Hollweg, 1972).

Some of the Alfvénic waves may steepen to give an "Alfvén shock" or a rotational discontinuity (Burlaga, 1971; Smith, 1973). In all Alfvénic disturbances one sees a change in the field direction if one moves *along* the average field direction. Parker (1963) discussed the reflection and transmission properties of sharp bends in the field. If an isotropic particle flux is incident on a discontinuity where the field magnitude increases ($B_2 >$

B_1), the net transmission is simply B_1/B_2. A similar result is obtained from conservation of the first adiabatic invariant in a *continuous* increase in field magnitude; in any case particles arriving with sufficiently large pitch angles will be reflected. Webb and Quenby (1974) show by trajectory calculations that field line kinks with *no* change in magnitude also exhibit reflection properties (of the order of 5% for 45° angle between the directions of the fields on both sides). One can therefore produce a random walk of particles back and forth along a multidiscontinuous field configuration. This effect of non-resonant interaction at large scale structures is complimentary to the small-angle resonant scattering (see below).

Micro-Scale Structures

Here we deal with time scales between 1 hour and 30 seconds (Burlaga, 1969a). An early result was the so-called "filamentary structure" of the IMF based on the observations of short time periods where field bundles of one direction were embedded in a field region of different direction (Ness *et al.*, 1966). The observed field aligned streaming of solar cosmic rays suggested the streaming of particles along field line filaments extending from sun to earth, with little or no coupling between the streaming in adjacent bundles (McCracken and Ness, 1966).

The discontinuous nature of the interplanetary field was confirmed later by an extended analyzis (Burlaga, 1969a, 1969b), but the concept of an aggregate of filaments was replaced by an ensemble of discontinuities themselves. On the average they are separated by ≈ 0.01 AU, corresponding to the average occurence of about 1 per hour. The distribution of time intervals between successive DCs resembles a Poisson distribution. There has been a long discussion on the nature of the discontinuities, tangential vs. rotational (see Burlaga, 1971; Smith, 1973; Fisk and Sari, 1973). Following the original definition of Burlaga (1969a), namely a change in the field direction by more than 30° between two consecutive measurements separated by 30 sec, Burlaga (1971b) has shown that the majority of discontinuities defined in this way are in fact tangential. On the other hand, Smith (1973) has established the existence of rotational discontinuities and found 44 RDs in 40 days of data. This number is a lower limit: the selection criterion required a subset of discontinuities which were relatively thick.

Martin *et al.* (1973) have studied abrupt changes in the interplanetary plasma velocity and magnetic field from 19 days' Pioneer 6 data. They show that these changes are predominantly Alfvénic in *high*-velocity streams, but that the majority of abrupt changes are not Alfvénic in a *low*-velocity solar wind. The period studied by Burlaga (1971b) which was characterized by the large relative abundance of TDs (see above) was a low-speed region with a low occurrence rate for Alfvénic changes.

There are fundamental differences between rotational and tangential discontinuities (RDs and TDs). Most important for us is that in contrast to the RDs which can be visualized as sharp bends in the field, there is no field component normal to the discontinuity surface for TDs, which means that the magnetic fields on both sides of the surface are not connected. Cosmic ray particles with Larmor radii *small* compared to the average distance between TDs (which applies to protons below a few hundred MeV) will in general not meet the discontinuity surfaces, unless they are transported across the average field by drift and perpendicular diffusion. These effects are however small over the distances involved here. Therefore, for the problem of cosmic-ray transport, the question how many discontinuities are tangential or rotational is crucial. This problem is not yet fully resolved, partly because of the difficulty of proper identification (see Burlaga, 1971; Smith, 1973).

Spectral Representation

So far we have discussed individual IMF structures in some detail. A method in which the nature of the field fluctuations is disregarded and the total variance of the fluctuations is split up into contributions from various frequency intervals is the power spectral analyzis. Power spectra were discussed e.g. by Jokipii and Coleman (1968); Sari and Ness (1969). In this representation, the difference between quiet and disturbed interplanetary conditions shows up as an order of magnitude difference in the spectral power. Over certain intervals, the spectra can well be represented by power laws f^{-q} with q between 1.5 and 2.0 in the frequency interval $10^{-4} \dots 10^{-1}$ Hz. Since to first order the fluctuations are frozen into the solar wind plasma (the Alfvén speed can be neglected in comparison with the bulk speed) it is possible to convert the measured frequency spectra to wave-number spectra in the radial direction.

Jokipii (1966) describes cosmic ray propagation in a weakly turbulent field configuration, namely an average field with superimposed small fluctuations. The elementary process is one of small changes in pitch angle; pitch angle diffusion is described by a Fokker-Planck equation, and the pitch angle diffusion coefficient is related to the magnetic field spectral power at that wave number which is in resonance with the particle spiral motion along the field. For small anisotropies in the pitch angle distribution, spatial diffusion along the average field results. Apart from a numerical factor of the order 1, one obtains for the mean free path $\lambda_{\parallel}$ along the average field (see Jokipii, 1971; Wibberenz, 1973, for details):

$$\lambda_{\parallel} \approx \frac{p^2}{4f(k)} \qquad (1)$$

where the spectral power $f(k)$ has to be taken at the "resonance" wave number $k=\Omega/v=B/P$. Here P=magnetic rigidity, v=velocity, Ω=gyration frequency of the energetic particles under consideration, B=(average) magnetic field strength.

In case of a pure power law, $f(k)\sim k^{-q}\sim P^{q}$ wo obtain the important result

$$\lambda_{\parallel}\sim P^{2-q} \tag{2}$$

The formalism has been extended (Jokipii, 1971, 1972; Hasselmann and Wibberenz, 1968) and applied to a number of cosmic ray propagation problems. We shall summarize some of the results in section 3.

An important modification came from the idea of Sari and Ness (1969) that tangential discontinuities contribute to the power spectrum above a certain wave number, but do not scatter cosmic ray particles below a certain rigidity (see discussion above). Sari (1972) has developed a method to subtract the discontinuities from the spectrum and to derive the cosmic ray diffusion coefficient from the fluctuations between discontinuities only. These results are further discussed by Fisk and Sari (1973) and Lanzerotti *et al.* (1973). It should be pointed out again, that Eqs. (1) and (2) and the remarks in the last paragraphs are the results of an approximation to the particle motion in turbulent magnetic field which has been questioned (see section 4).

Temporal and Longitudinal Variations

From a subset of magnetic field data it had been concluded (Hedgecock *et al.*, 1972) that there are no significant changes in the spectral power level with the solar cycle. However, a careful analyzis of a large amount of data by Hedgecock (1974) has revealed that with increased solar activity the power in the transverse field fluctuations also increases, mainly at frequencies less than 10^{-5} Hz. The relevance for cosmic-ray modulation in the neutron monitor range is extensively discussed by Hedgecock (1974).

On a day-to-day basis the variation is much larger.

It should be noted that on the scale below 1 hour, the magnetic field for some periods does not at all look turbulent, but may be very smooth on both sides of a tangential discontinuity. These are the so-called "quiet" interplanetary conditions. Sari (1972) has shown that in this case the total IMF power spectrum for frequencies between 10^{-4} and 10^{-2} Hz is to a large degree determined by tangential discontinuities and shows a spectral slope close to f^{-2}. Under "disturbed" conditions there is particular increase in the fluctuations *between* the discontinuities. In this case the spectral slope is close to $f^{-1.65}$.

It is interesting to speculate whether the characteristic of an IMF region as "quiet" or "disturbed" is a local property of the field, (e.g. connected with local plasma instabilities) or whether it extends all the way along a certain field line bundle, back to the Sun and further out beyond the orbit of earth.

It is obvious that cosmic rays are very suitable to distinguish between these alternatives, because their propagation characteristics are determined by the integral effects of disturbances along the magnetic field between source and observer. The sector pattern of the interplanetary magnetic field and the high-speed streams within the sectors seem to form the main basis for ordering the degree of disturbance of the IMF.

An oversimplified view (see Burlaga, 1972; Martin *et al.*, 1973, for details) suggests the following pattern. The leading edge of a high-speed stream has the highest degree of disturbance; at present the nature of the disturbances is difficult to interpret. The high-speed stream itself is dominated by large-amplitude Alfvénic changes down to scales of about 1 minute. The amplitude of the waves decreases on the trailing edge of the high-speed stream. The subsequent low-velocity region is magnetically very quiet and possibly dominated by tangential discontinuities. This region is most probably a candidate for the "scatter-free" propagation (see below). As far as the Alfvén waves are concerned, their pattern with respect to the high-speed streams is predicted theoretically by Richter (1974) who studies the propagation of Alfvén waves of solar origin in an azimuthally-dependent solar wind. Waves of the largest amplitude occur in the stream-stream interaction region. So this is partly a local effect, and the high level of disturbance will *not* extend all the way back to the sun. So we can in principle still have relatively fast propagation of solar cosmic rays in spite of a high *local* level of the IMF fluctuations. This would be one possibility for the poor correlation between the locally observed IMF power spectrum and the propagation of solar cosmic rays (see Webb *et al.*, 1973, and the discussion in section 3).

It should be pointed out that we will not dicuss in this paper the relation of interplanetary shocks to cosmic-ray propagation.

3. Results of the Diffusion Model

3.1 The Model and Its Parameters

As discussed in the introduction, the diffusion model was based on a phenomenological approach before interplanetary magnetic field measurements had been performed. According to Parker (1965) cosmic ray transport is due to diffusion, convection, and adiabatic deceleration. The particle differential density $U(T, r, t)$ as a function of kinetic energy T, radial distance r from the sun and time t satisfies the equation

$$\frac{\partial U}{\partial t} = \frac{\partial}{\partial x_{\parallel}}\left(K_{\parallel}\frac{\partial U}{\partial x_{\parallel}}\right) - \boldsymbol{V}\nabla U - CU\nabla\boldsymbol{V} \tag{3}$$

The cosmic ray streaming is given by

$$\boldsymbol{S} = CU\boldsymbol{V} - K_{\parallel}\frac{\partial U}{\partial x_{\parallel}}\boldsymbol{B}_0 \tag{4}$$

(for details see Axford, 1972; Jokipii and Parker, 1970). Here $K_{\parallel}$ is the diffusion coefficient parallel to the average magnetic field, $\boldsymbol{V}$ the solar wind velocity, $\boldsymbol{B}_0$ the unit vector in magnetic field direction, pointing outwards from the Sun, $C = 1 - \frac{1}{3U}\frac{\partial}{\partial T}(\alpha TU)$ the Compton-Getting factor with $\alpha = (T + 2m_0c^2)/(T + m_0c^2)$, m_0 = rest mass of particles.

Eqs. (3) and (4) have been simplified as compared to the general expression by considering only particle diffusion along the magnetic field, resulting in the diffusive flux $K_{\parallel}\frac{\partial U}{\partial x_{\parallel}}$ in the direction of the field $\boldsymbol{B}_0$, with $x_{\parallel}$ the spatial coordinate along the field (positive for increasing distance from the sun). If the large-scale magnetic field configuration is known, it is possible to relate $x_{\parallel}$ along the field to the radial distance r from the sun. This means that alternately we can replace Eq. (3) by

$$\frac{\partial U}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(K_r r^2 \frac{\partial U}{\partial_r}\right) - \boldsymbol{V}\nabla U - CU\nabla\boldsymbol{V} \tag{3a}$$

in a spherically symmetric problem or if in a problem with azimuthal gradients we are only interested in the density distribution along a field line bundle.

Here $K_r = K_{\parallel}\cdot\cos^2\psi$ with ψ the spiral angle between the magnetic field direction and the radius vector from the Sun. Neglect of diffusion perpendicular to the field is justified by a number of observations for solar cosmic rays (see Nolte and Roelof (1973a), Reinhard and Wibberenz (1974a), McKibben (1973), for discussion). The treatment of the diurnal variation of galactic cosmic rays by Subramanian (1971) shows that in general we also have $K_{\perp}/K_{\parallel} \ll 1$ in the range of several GeV.

The essential unknown parameter which determines the solution of Eq. (3) for given boundary conditions is the diffusion coefficient $K_{\parallel}$ which will in general depend on the particle properties, on the time of observation, and on the location in space.

a) Ordering in terms of particle properties is considerably simplified by the fact that $K_{\parallel}/v$ (v = particle velocity) is the same for particles of the same gyro-radius, so that the mean free path $\lambda_{\parallel} = 3\ K_{\parallel}/v$ only depends on rigidity P (see also Eq. (2)).

b) We distinguish long- and short-term time variations. For the 11-year galactic cosmic ray variation one takes energy spectra $U(T)$ representating averages for a certain phase in the solar cycle. A comparison is made with spherically symmetric solutions of Eq. (3a) for suitable choices of $K_r(r)$. For the propagation of solar cosmic rays one has to take azimuthal variations into account by specifying $\lambda_{\parallel}(x_{\parallel}, \phi)$, with ϕ the solar longitude of the root of a field line bundle, close to the sun, and $x_{\parallel}$ the distance along this field configuration. For the radial dependence one parametrizes the form of $\lambda(r)$, e.g. by a power law $\lambda(r) = \lambda_E(r/r_E)^n$, with λ_E the "local" mean free path at $r = r_E = 1$ AU.

This smooth dependence is in some cases supplemented by an abrupt change in the mean free path at some outer distance R.

In galactic cosmic ray modulation studies, R has been called the "size of the modulation region"; in solar cosmic ray events, R has been called a "free escape boundary". We take the viewpoint here that if we average conditions over time constants large compared with a solar rotation, both determinations of R from totally different sets of observations — solar and galactic cosmic rays — should finally lead to the same value of R. The introduction of R is a mathematical idealization for a physical situation where over a certain spatial distance the mean free path increases considerably, so that scattering effects become negligibly small for $r \geq R$: no solar cosmic rays are scattered back into the inner solar system once they have reached R, and the galactic cosmic ray intensity begins to decrease only if one enters the modulation region $r \leq R$.

We see the great importance of the theoretical approaches from which the local value λ_E and the radial dependence might finally be obtained via the IMF properties. If it should turn out that in a certain rigidity range the particle scattering is mainly determined by Alfvén waves the theoretical studies on the propagation of Alfvén waves will supply an answer. Jokipii (1972) obtains $\lambda_r(r) = \text{const}$ in a special propagation model for Alfvén waves where all wave vectors are parallel to the magnetic field. This is in contrast to results of the WKB-approximation (see Völk *et al.*, 1974), so it will need modification. Völk *et al.* (1974) show that in an axially symmetric interplanetary medium the power at a distance of 1 AU from the sun is concentrated in wave vectors pointing *radially* away from the sun. This leads to $\lambda_r(r) \sim r^3$ for large distances from the sun. However, the experimental results on Alfvén waves (Belcher and Davis, 1971) do not agree with the large radial asymmetry of the k-vector-distribution. As shown by Richter (1974) the amplitude and the refraction of Alfvén waves depend on the location with respect to the high speed solar wind streams. Both the amplitude and the wave vector distribution determine the value of the mean free path λ in a way which is not yet totally clear. In the subsequent sections we shall concentrate on the results derived experimentally by fits of cosmic-ray observations to the diffusion-convection model.

3.2 Solar Cosmic Ray Events: General

One of the reasons for the succesful use of the diffusion model for the description of solar cosmic ray events was the observation that many events "look diffusive", i.e. they show a relatively smooth time-intensity profile with a fast increase to a well defined intensity maximum and a subsequent slower decrease. These profiles could be explained by a delta-function injection of particles close to the time of the H_α- or X-ray maximum of the original flare and a random walk of particles in space with a mean free path typically in the range 0.02... 0.10 AU (see Krimigis, 1965; Burlaga, 1967). In this early work the diffusion model was used to describe adequately the intensity-time profile of solar events, and in estimating the mean free paths simple assumptions were made:

the radial dependence is a simple power law, $\lambda(r) \sim r^n$;

convective effects, i.e. the last two terms in Eq. (3), are neglected;

propagation effects close to the sun are neglected.

This situation changed when the observations were extended to lower energies and when simultaneous intensity and anisotropy measurements throughout large parts of solar events became available. The anisotropy measurements on board Pioneers 6—9 and Explorers 34 and 41 (see McCracken *et al.*, 1967, 1971; Rao *et al.*, 1971) showed that both diffusion and convection play an important role in the later phases of the events. Theoretical interpretations of the results in terms of the diffusion-convection model have been attempted by Rao *et al.* (1971), Ng and Gleeson (1971). The negligible perpendicular diffusion is inherent in the interpretation. The anisotropy vector $\boldsymbol{\delta}$ is related to the streaming $\boldsymbol{S}$ in Eq. (4) by $\boldsymbol{\delta} = 3\,\boldsymbol{S}/vU$, and can thus be written as a sum of a convective and diffusive anisotropy,

$$\boldsymbol{\delta} = \boldsymbol{\delta}_c + \boldsymbol{\delta}_d \qquad (5)$$

with

$$\delta_c = 3\,CV/v, \; \delta_d = \lambda_{\parallel} \frac{1}{U} \frac{\partial U}{\partial x_{\parallel}}. \qquad (6)$$

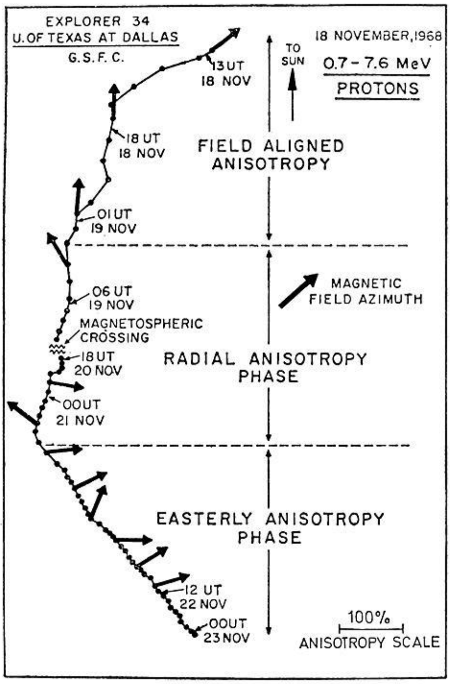

Fig. 3. The hourly anisotropy vector diagram for the flare event of November 18, 1968. The direction of the magnetic field at approximately 6 hour intervals, is also indicated in the figure with an arrow. (After Allum *et al.*, 1974)

Let us summarize the main features of various phases in a longlasting solar event following Allum *et al.* (1974). Fig. 3 shows the hourly anisotropy vector diagram and the characteristic three phases for 0.7—7.6 MeV protons during the 18 Nov 1968 solar event.

a) In the *first phase* the anisotropy is field-aligned, $\delta_c \ll \delta_d$. Diffusion dominates, $\boldsymbol{\delta}$ is approximately parallel to $\boldsymbol{B}$. It is noteworthy that this also holds if the field deviates largely from the nominal spiral direction, e.g. during one of the long lasting "kinks" discussed in relation with Fig. 2. The cosmic-ray density is decreasing towards the sun, $\partial U/\partial x_{\parallel} < 0$.

b) In the *second phase* (radial anisotropy), $\delta_d \approx 0$. The direction of $\boldsymbol{\delta}$ is insensitive to the momentary field direction, the measured anisotropy amplitude as an average over 5 solar events is $9.8 \pm 1.0\%$, which compares reasonably well with the expected theoretical value $\delta_c = 12.4\%$ (for mean particle speed $v = 0.063\ c$, $V = 390$ km/sec, $C = 2$). These results imply that the density gradient $\partial U/\partial x_{\parallel}$ is small or close to zero in this phase and that the radial anisotropy is the result of convection alone.

c) In the *third phase* (easterly anisotropy) the anisotropy is directed from the direction 38.7 ± 2.40 E. The anisotropy amplitude varies between 0.5% and 30% as the magnetic azimuth changes from 360° to 250°, but it is very remarkable that the anisotropy *direction*, which is normal to the mean spiral magnetic field direction, is *invariant* over a wide range of particle speed ($0.06 \leq \beta \leq 0.56$) and also *independent* of the momentary local magnetic field azimuth. In this phase both δ_c and δ_a contribute to the total anisotropy δ. A positive density gradient (which is explained by the convective expulsion of the cosmic-ray population due to convection with the solar wind) leads to a diffusive streaming of particles back towards the sun which combines with the radial convective streaming to the easterly anisotropy. Though the general pattern of the anisotropy behaviour (field-aligned, radial, easterly) is qualitatively accounted for by the diffusion-convection model, the invariance of the anisotropy direction in the easterly phase is not predicted by contemporary theories (see Allum *et al.*, 1974). The authors point out that the last easterly phase is only seen in the *late* phase of large solar particle events. "Late" can mean up to 10 days after the flare, from which we conclude that i) one needs a large event to see residual particle fluxes after such a long time, ii) no subsequent large particle events must disturb the pattern, and iii) the mean free path in interplanetary space has to be sufficiently small to keep the particles within the solar cavity for sufficiently long time.

So the observations just discussed clearly discern one pattern of solar cosmic ray events; but due to varying solar and interplanetary conditions there are also other event structures observed as we shall see below.

We shall split up the discussion of solar cosmic-ray events into the initial phase (until slightly beyond the intensity maximum) and the decay phase. The reason is, that to good approximation the initial phase is determined by the distribution of scattering mean free paths between the sun and the observer, the decay phase by the behaviour of λ beyond the observer.

3.3 Solar Cosmic Ray Events: Initial Phase

Let us start the discussion with the results of Lupton and Stone (1973). Though their model contains diffusion perpendicular to the average magnetic field ($K_\perp \neq 0$), their solutions which are separable in radius and azimuth are not strongly influenced by $K_\perp$ for flares on the western hemisphere on the sun. They have used a model where K_r =const up to a free escape boundary at $r = L$. The results for two solar particle events on the Western solar hemisphere, converted to a mean free path as a function of rigidity, are contained in Fig. 4 together with a number of other data. λ_r is slightly decreasing as a function of rigidity, a typical value is 0.03 AU.

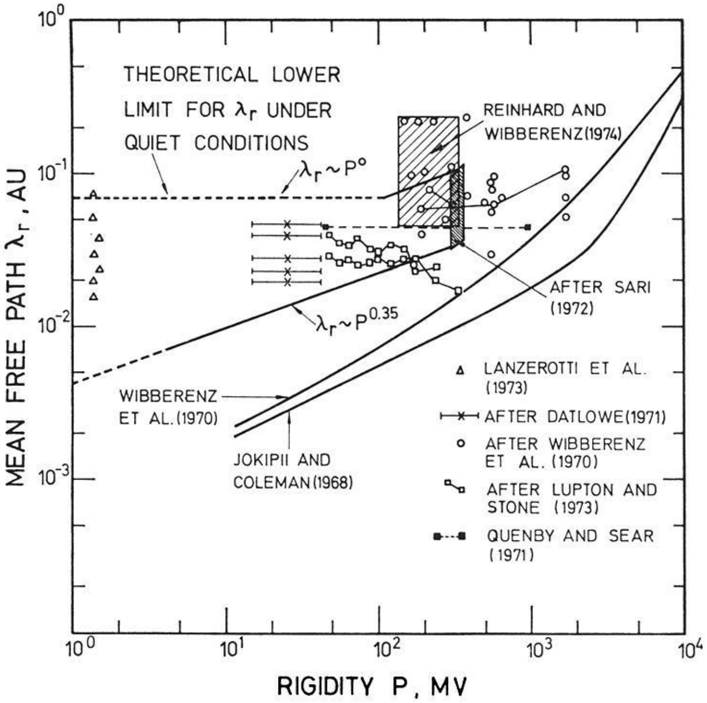

Fig. 4. Determination of the cosmic-ray scattering mean free path λ_r from the time-to-maximum-intensity t_m for individual solar events, in comparison with theoretical estimates from magnetic field power spectra

Lupton and Stone (1973), by fitting the whole measured event profile have shown that the assumption $\partial K_r/\partial r = 0$ allows to fit both the initial and the decay phase of events, in contrast to e.g. $K_r(r) \sim r$. In estimates of the mean free path from solar event profiles we shall use this assumption $K_r = \text{const}$ for $r \leq L$ from now on. It allows simple estimates of K_r from the observed time of maximum intensity. At least one can use diffusion coefficients derived in this way as a measure of the *average* scattering conditions between sun and earth, keeping in mind that deviations in the *local* mean free path can arise should the radial dependence deviate greatly from $\lambda = \text{const}$.

Before continuing let us estimate the importance of convective effects. From the last term in Eq. (3) we get $-(2\, CV/r)U = -U/T_{ad}$ with a time constant T_{ad} characterizing the influence of adiabatic energy changes. For power law energy spectra with slopes between -2 and -3 we obtain T_{ad} of the order of one day. So we should be able to neglect convection in the solutions of Eq. (3a) for times up to about 10 hours following the injection at the sun. This means one should get a reasonable estimate for K_r from the time t_m to maximum intensity in this case. For delta-function injection, the solution of (3a) with only the diffusive term on the r.h.s gives $t_m = r^2/6\, K_r$ or with $K_r = \beta c \lambda_r/3$ we simply obtain $\lambda_r = r^2/2\, \beta c t_m$. We summarize in Fig. 4 a few of the results for λ_r as a function of rigidity based on this method. Wibberenz *et al.* (1970) have summarized data from solar proton events on the Western hemisphere on the sun, Lanzerotti *et al.* (1973) data from solar electron events around 1 MeV. The t_m-values given by Datlowe (1971) from relativistic electrons have been converted to λ_r-values by the same method.

In these estimates of λ_r delays or finite injection periods occuring close to the sun have been neglected. Therefore, in Fig. 4 only Western hemisphere solar events have been included. However, there is evidence meanwhile that *solar* propagation effects may also play a role in solar events on the Western solar disk (Simnett, 1972; Reinhard and Wibberenz, 1974a). We have included in Fig. 4 results by Reinhard and Wibberenz (1974a). They have analyzed the velocity dispersion and the onset times of 45 solar proton events in the range 10—60 MeV and found that a velocity independent delay time (which is attributed to a drift process in the solar corona) has to be subtracted from the time to maximum intensity t_m, before one can estimate the interplanetary propagation effects. From this study, one obtains an average mean free path of the order of $\bar{\lambda}_r = 0.1$ AU in the rigidity range 140—340 MV (see Fig. 4).

For comparison the mean free path as derived from measured IMF spectra according to the resonance scattering formalism (Jokipii, 1966, Hasselmann and Wibberenz, 1968) is plotted in Fig. 4 after Jokipii and Coleman (1968); Wibberenz *et al.* (1970). The difference between the solar event data and the magnetic field derived data, when the full spectral power is inserted, has been observed and discussed earlier (see Wibberenz *et al.*, 1970; Quenby and Sear, 1971b; Wibberenz, 1973). This disagreement becomes more pronounced at lower rigidities. In section 2 we mentioned the necessity to subtract that part of the power spectrum which is due to tangential discontinuities (Sari and Ness, 1969). Also included in Fig. 4 are results based on Sari (1972). We discuss one application of his results following Lanzerotti *et al.* (1973).

Sari (1972) has calculated daily interplanetary power spectra from Pioneer 6 IMF measurements during four solar rotations, for the total field variations as well as from considering only the field variations between the discontinuities. He used these "between spectra" to estimate the cosmic-ray diffusion coefficient for 50 and 70 MeV protons. 90% of all the diffusion coefficients fall into the range indicated in Fig. 4 by the hatched area in the rigidity interval slightly below 400 MV. The lower value corresponds to disturbed interplanetary conditions, where the spectral slope of the "between spectrum" is $\sim f^{-1.65}$ up to frequencies of 10^{-2} Hz. According to Eq. (2) this allows to extrapolate the mean free path with an $\sim P^{0.35}$ dependence down to rigidities in the MV range.

The upper value around 0.1 AU at $\approx$400 MV corresponds to quiet interplanetary conditions. Here the extrapolation to lower rigidities is less straightforward (see Lanzerotti *et al.*, 1973, for more details). The $\lambda = \text{const}$ curve should be taken as a *lower* limit of the mean free path under quiet conditions, since it is not clear which part of the spectrum in this range is due to tangential discontinuities. The overall agreement between solar event and IMF spectra derived points looks quite satisfactory. However, we have outlined the *range* of variation of mean free paths, but in view of the large variations, one certainly requires a comparison of data where the magnetic field power spectrum is analyzed at the *same* time when the solar event is observed. It has been shown that periods exist where the magnetic field is quiet for a long time and the solar cosmic ray propagation is indeed very fast (Wibberenz, 1971; Wibberenz *et al.*, 1973). The reverse is not necessarily true. A systematic study has been undertaken by Webb *et al.* (1973) and gives further insight into the nature of the fluctuations and the possible radial dependence. They have analyzed interplanetary magnetic field and plasma data during the time of three solar events and base numerical solutions of the full transport equation on estimates of the local mean free path as derived from the magnetic field data combined with various radial dependences $\lambda(r)$. Under the assumption $\lambda_r = \text{const}$ the time to maximum t_m for 1—13 MeV protons would result in $\lambda_r = 0.03$ AU for the 24 January 1969 event, $\lambda_r = 0.054$ AU for the 17 March 1969 event. These figures are based on full solutions of the transport equation including convection. However, mean free paths calculated from the power spectra measured at the *same* time via the resonant-scatter theory (Jokipii, 1966) come out about a *factor of 10 smaller*. This could be reconciled with the solar proton data only if one assumes a r^{-3}-dependence of the mean free path between sun and earth. Even if one argues that part of the large power might be produced locally, namely in the turbulent interaction region in front of a high speed plasma stream, the required r^{-3} dependence seems rather unlikely. No attempt has been made in the estimate by Webb *et al.* (1973) to subtract discontinuities from the spectrum. It seems doubtful anyhow whether removal of large discontinuities can remove the discrepancy, because the data (Sari, 1972; Fisk and Sari, 1973) do not support the view that in this frequency domain the contribution from discontinuities can amount up to 90% under *disturbed* conditions.

Webb *et al.* (1973) have also explored the diametrically opposite possibility, in extension of an earlier suggestion by Quenby and Sear (1971), namely that all magnetic power is in discontinuous changes in $|\boldsymbol{B}|$ along the flux tube of propagation (rotational discontinuities); in this case the results look more reasonable, but even here the local value of λ_r is probably underestimated.

The individual data points in Fig. 4 were based on the assumption of negligible solar propagation effects. In the rigidity range ≈ 130—300 MV the average mean free path has been lifted to about $\bar{\lambda}_r = 0.1$ AU according to the subtraction of coronal propagation effects (Reinhard and Wibberenz, 1974a). It is very probable, that part of the variation in the other data points in Fig. 4 is also due to coronal transport processes. Simnett (1974) in his review on relativistic electron events discusses various classes of events and presents evidence for the delayed release of electrons from the sun.

Long-lasting large anisotropies in solar events also called for finite solar injection processes (e.g. McCracken *et al.*, 1967). Palmer *et al.* (1974) discuss the solar event of 20 April 1971, in which the anisotropy for 21—60 MeV protons remained large and field-aligned well into the decay phase. A Monte Carlo simulation of the propagation led to a mean free path along the field of 1.6 AU; the results could not be reconciled with impulsive solar injection.

Another instructive example for the long-lasting 18 November 1968 event is discussed by Schulze *et al.* (1974). They show that the size of the anisotropy for 21—60 MeV protons for the first day after the solar flare is not consistent with a delta-function solar injection. A fit to both the intensity and anisotropy profile was obtained by a finite injection period of 10 hours and a value of the mean free path $\lambda_r = 0.15$ AU for 21—60 MeV protons.

The position that in many instances the observed time structures of solar events are almost exclusively determined by solar injection processes has been strongly advocated by Roelof (1973). In this picture, >0.3 MeV protons propagate without any scattering in the inner solar system. It should be noted that there are indeed quite a few solar proton events where after subtraction of coronal propagation effects the remaining interplanetary propagation time is very small. Fig. 8 in Reinhard and Wibberenz (1974a) shows data points where the "average interplanetary travel distance c_2" is only $vt_m \approx 2$ AU, which is close to the condition of scatter-free propagation. The so-called "scatter-free" propagation was first noted for solar electrons in the >40 keV energy range (Lin, 1970). For the large amount of observational data on non-relativistic electrons the reader is referred to the review by Lin (1974). He has also summarized values for the diffusion coefficient for electron events. They span the range from $\approx 10^{21}$ cm^{2}sec^{-1} for "diffusive" events to $\approx 10^{24}$ cm^{2}sec^{-1} for highly "scatter-free" events. This corresponds to a range of mean free paths between 0.02 AU and $\gg 1$ AU in the rigidity range below 1 MV (left of the scale in Fig. 4). Lin (1974) discusses the scatter-free electron events in terms of the possibly very low power at high frequencies or, alternately, in terms of a spectral slope ≥ 2 of the magnetic field spectrum at high frequencies (see Earl, 1974). If the f^{-2}-dependence of the IMF power spectrum in the frequency range 0.1—1 Hz under quiet conditions (see Childers and Russell, 1972) is due to tangential discontinuities only, the scatter-free propagation is easily explained because the electrons with their very small Larmor radii will not meet these disturbances (see the discussion in Section 2).

3.4 Solar Cosmic Ray Events: Decay Phase

It has often been observed that the decay of solar cosmic ray events is exponential at late times, and theoretical explanations have been given in terms of a "free escape boundary" (see section 3.1) which would have to be located between 2 and 3 AU (Burlaga, 1967; Forman, 1971; Lupton and Stone, 1973). Ng and Gleeson (1971) have shown that for sufficiently small diffusion coefficient the convective effects lead to a decay phase which is hardly distinguishable from an exponential. This limit is at about 10^{20} cm^2/sec at $r=1$ AU (Gleeson, private communication). For this value of the d.c. the local transport would be almost totally convective. It is interesting to compare this value with an estimate by Allum *et al.* (1974). Based on a specific model for the late easterly anisotropy, they get an indirect information on the radial density gradient from a correlation between the decay time and the magnetic field azimuth of the order of 1000%/AU for 0.7—7.6 MeV protons. Combined with the measured anisotropy this allows to estimate the parallel diffusion coefficient to $K_{\parallel} \approx 1.3 \cdot 10^{20}$ cm^{2}sec^{-1} ($\lambda_r \approx 0.007$ AU at $P=56$ MV). The above explanation of exponentially observed decay phases by a low value of the d.c. looks rather attractive, because the observations out to the orbit of Jupiter (see section 2) did *not* indicate a change in the disturbance level of the IMF around 2—3 AU as would be demanded by the existence of a sharp or gradual change of the cosmic-ray d.c. in this region of space. Also, the small value of K would be consistent with the long delay between the flare and the maximum intensity for the long lasting events under study. Note however that the above considerations are based on a propagation model with burst-like injection at the sun; long lasting solar injection can modify the time to maximum of an event as well as the decay phase. The influence of exponentially decaying solar injection profiles (Reinhard and Roelof, 1973; Reinhard and Wibberenz, 1974b) is presently being studied. As mentioned already, Palmer *et al.* (1974) discussed the solar event of 20 April 1971, in which the injection of particles at the sun probably decayed with a e-folding time of 7 hours and in which a Monte Carlo simulation of the propagation led to a mean free path along the field of 1.6 AU.

We had discussed examples for a large variability in the propagation conditions for *solar* events and turn now to some results from *galactic* cosmic rays, which should give indications for conditions averaged over longer time periods.

3.5 Galactic Cosmic Rays: Long Term Modulation

Let us start by noting that the cosmic-ray streaming in the several GeV range, as typical for neutron monitor energies, can be visualized in a similar way as discussed for lower energy solar cosmic rays and described by Eq. (4). This is the basis for the explanation of the normal diurnal variation as seen from the earth (see Subramanian, 1971, for discussion). Hashim *et al.* (1972) point out that also for the enhanced diurnal variation (which characterizes disturbed interplanetary conditions) and for large non-equilibrium anisotropies during various phases of Forbush decreases the cosmic-ray streaming can be described as a sum of the radial convective streaming away from the sun and diffusive streaming parallel to the direction of the momentary interplanetary magnetic field.

It is one result of the studies of the galactic cosmic ray diurnal variation that under undisturbed conditions the *radial* component of the streaming $\boldsymbol{S}$ is zero. Applying this to Eq. (4) for spherical symmetry we obtain

$$CVU = K_r \frac{\partial U}{\partial r} \tag{7}$$

Gleeson and Axford (1968) have provided a theoretical basis for the vanishing radial streaming, the so-called force-field approximation, which can be used to describe the long-term modulation of galactic cosmic rays for kinetic energy > 150 MeV (see Gleeson and Urch, 1973). In this range, the results obtained from Eq. (7) are to a very good approximation similar to the results of the full transport equation (3a). Many studies of the 11 year modulation have been performed, using either full solutions of Eq. (3a) or the force-field approximation (7) (see Gleeson, 1973, for details).

Full solution of the problem in this spherically symmetric form requires, a) the specification of the galactic cosmic ray spectra outside the boundary R of the modulation region (the local interstellar spectra), b) the specification of the function $3K_r/v = \lambda_r(P, r, t)$ in its dependence on particle rigidity P, location r within the modulation region, and phase t in the 11 year solar cycle. Important tools in these studies have been, 1. estimates of the local interstellar electron spectrum from radio observations of the galactic synchrotron emission, 2. the requirement that the modulation for electrons, protons, and Helium nuclei for a given time period t has to be described by the one unique function $\lambda_r(P, r)$, which for given solar wind speed and boundary conditions determines the solution of the transport equation.

In the discussion of results we follow the presentation by Gleeson and Urch (1973) which is particularly useful for comparison with the results in sections 3.3 and 3.4. If the diffusion coefficient is separable in the form $K(P, r) = \beta K_1(r)\, K_2(P)$, or, to relate it to our previous notation

$$\lambda_r(P, r) = \frac{3}{c}\, K_1(r)\, K_2(P) \tag{8}$$

the total modulation for $r \leq R$ can be described by the "modulation parameter" Φ, which is independent of rigidity, as

$$\Phi(r) = \int_r^R \frac{V(r')}{3K_1(r')}\, dr' \tag{9}$$

Taking the solar wind velocity as constant, we can relate the local mean free path $\lambda_r(P, r_E)$ to the modulation parameter by

$$\lambda_E \equiv \lambda_r(P, r_E) = \frac{V}{c}\, \frac{K_2(P)}{\Phi(r_E)}\, K_1(r_E) \int_{r_E}^R \frac{dr'}{K_1(r')} \tag{10}$$

Here the rigidity dependence of the mean free path is contained in the term $K_2(P)$. Similar to the situation in solar cosmic rays, the local mean free path λ_E is determined only if the *form* of the radial dependence $K_1(r')$ is known. However, it is a characteristicum of the force-field approximation, as expressed in Eq. (9) or (10), that the total amount of modulation only depends on the "total number of mean free paths" $\int dr'/K_1(r')$, not on the distribution within the modulation region. One way to describe the scattering properties of the region beyond the orbit of earth is then to artificially assume that $K_1(r') = \text{const} = K_0$ for $r_E \leq r' \leq R_{\text{eff}}$ and to define R_{eff} as an "effective size of the modulation region" by letting $(R_{\text{eff}} - r_E)/K_0 = \int_{r_E}^{R} dr'/K_1(r')$. With this definition we obtain

$$\frac{\lambda_E}{R_{\text{eff}} - r_E} = \frac{V}{c}\, \frac{K_2}{\Phi} \tag{10a}$$

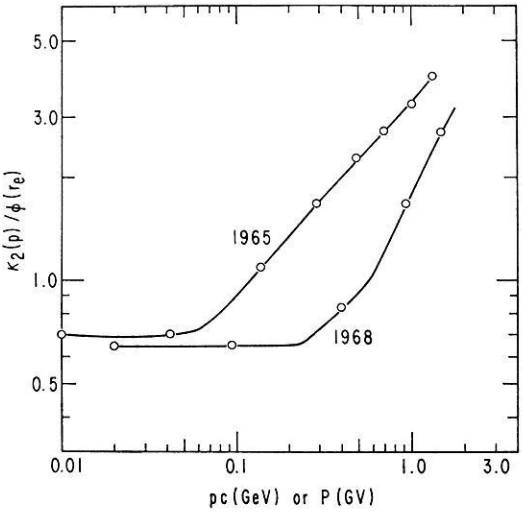

Fig. 5. Functions K_2/Φ for 1965 and 1969 as obtained by Gleeson and Urch (1973). Note that this function is proportional to the mean free path λ_r under the assumption of separability (see Eqs. (8) and (10a) in the text)

The ratio K_2/Φ (both quantities have the dimension of rigidity) has been determined by Gleeson and Urch (1973) from the demodulation of electrons for two periods in the solar cycle and is reproduced in Fig. 5. V/c with $V=$ solar wind speed is of order 10^{-3}, K_2/Φ is of order 1. (Fig. 5) and we see that we need about 10^3 mean free paths between the earth and the outer boundary in order to explain the galactic cosmic ray modulation. If at $P=100$ MV we take $\lambda_E=0.1$ AU as a representative value from Fig. 4, we get an effective size of the modulation region of $R_{\text{eff}}\approx 100$ AU. Of course one of many other alternate solutions if $K_1(r')$ depends strongly on r' might by a "diffusive shell" somewhere beyond the earth, extending say between 5 and 10 AU where the mean free path then would be as small as 0.005 AU.

It should be noted that implicit in the assumption of separability of the d.c. in the form of Eq. (8) is also the fact that R or R_{eff} does *not* depend on particle rigidity. As a result of this assumption the shape of the K_2/Φ-curves in Fig. 5 is the same as the functional dependence of the mean free path on rigidity. The "1968" curve which is close to solar maximum conditions shows a constant mean free path below about 300 MV; this agrees rather well with the tendency of solar event derived data in Fig. 4. The small solar cycle variation at the lowest rigidity range in Fig. 5 reflects the small change in the electron modulation at low rigidities (see e.g. Lezniak and Webber, 1971). The transition rigidity to a steeper dependence of the mean free path on rigidity increases with increasing solar activity; this is inherent to most fits of the long term galactic cosmic ray modulation by the diffusion-convection model (see Garrard *et al.*, 1973, for a summary of theoretical fits for the time periods between 1965 and 1970 by various authors).

3.6 Galactic Cosmic Rays: Radial Gradients

The experimental results had been conflicting for some time (see O'Gallagher, 1972), and theoretical calculations had allowed a wide range of alternative predictions (see Urch and Gleeson, 1972 b). Meanwhile the situation has changed somewhat: all recent results agree in the sense that the gradients are "small". Webber and Lezniak (1973) point out various possibilities to obtain a small gradient theoretically. We will only discuss here the case of negligible radial streaming (Eq. (10)), when the gradient is directly related to the diffusion coefficient by $G_r \equiv \dfrac{1}{U} \dfrac{\partial U}{\partial r} = CV/K_r$.

Webber *et al.* (1973) report gradient measurements for electrons in the energy range 2 to 8 MeV. The comparison of Pioneer 8 and IMP-4 gives a gradient of $+25 \pm 20\%$ between 1.0 and 1.1 AU for the first half of 1968; the Pioneer 9/IMP-4 comparison between 0.75 and 1.00 AU gives a radial gradient of $3 \pm 5\%/\mathrm{AU}$ in January-February 1969. So the gradients might be even consistent with zero. Webber *et al.* (1973) conclude that in the limit where $\delta_r = 0$, a gradient $\leq 10\%/\mathrm{AU}$ would correspond to a scattering mean free path $\lambda_r \geq 0.05$ AU (see Fig. 4 for comparison).

Gradient measurements for protons and Helium nuclei on Pioneers 8 and 9 in 1968/1969 are discussed by Webber and Lezniak (1973). Direct implications on the local d. c. are difficult to obtain. Taking only the result for the 800—1200 MeV differential proton channel, where C is close to 1, we obtain from the $20 \pm 12\%/\mathrm{AU}$ reported gradient a range of mean free paths of $\lambda_r = 0.013 \ldots 0.052$ AU for a rigidity around 1.5 GV.

Pioneer 10 measurements on the way out to Jupiter have led to gradient results from three different experiments. The so-called integral gradients refer to data from all particles above energy thresholds in the region 60...80 MeV/nucleon; the largest contribution to the counting rates comes from protons in the GeV-range. Van Allen (1972) reports a zero gradient with an uncertainty of $\pm 1\%/\mathrm{AU}$. Teegarden *et al.* (1973) obtain an integral proton gradient of $2.4 \pm 0.3\%/\mathrm{AU}$ over the radial distance 1—2 AU. McKibben *et al.* (1973) derive a preliminary value of $4.5 \pm 1.0\%/\mathrm{AU}$ over the radial range 1—2.8 AU.

Let us take $G_r = (2 \pm 2)\%/\mathrm{AU}$ simply to get an estimate for K_r. With $C = 1.5$ and $V = 400$ km/sec we would obtain $\lambda_r = 0.29\{^{+\infty}_{-0.14}\}$ AU for GeV protons. This is not a very definite result; the lower values are consistent with the values of the mean free path derived from solar proton propagation (see Fig. 4); the zero gradient would correspond to locally scatter-free propagation. The reader is referred to the various papers reporting radial gradient measurements (see above) for a view on the data from which the results have been obtained and for a discussion of the difficulties in deriving reliable values.

4. Limitations of the Diffusion Model: New Propagation Concepts

The majority of the evidence summarized in section 3 points to a relatively large average value of the scattering mean free path. With "large" I mean $\lambda_{\parallel} \approx 0.1$—$0.2$ AU for rigidities below a few 100 MV, with a further increase to higher values above some critical value P_c, where P_c varies with the solar cycle.

In the introduction we had formulated the hope for a "unified view" of cosmic-ray propagation in the interplanetary space by using the diffusion model and by specifying the scattering mean free path as a function of rigidity, radial distance from the sun, and time; the time dependence should include azimuthal variations during one solar rotation as well as long term variations during the solar cycle.

Mathews *et al.* (1971) had pointed out that the solar wind parameters which ought to cause changes in the magnitude of the modulation (magnitude and spectral power of the IMF, solar wind speed) show little variation between solar minimum and solar maximum. We mentioned in section 2 the results by Hedgecock (1974), indicating spectral changes with the solar cycle at low frequencies. Hedgecock (1974) finds a 25% increase in the frequency band 10^{-6} to 10^{-4} Hz, correlated with an 8% reduction in the high-latitude neutron monitor intensity. However, the spectral changes at higher frequencies are less pronounced. This still leaves room for the interpretation of Hedgecock *et al.* (1972) that the solar wind emitted from solar latitudes in the activity belt should show larger variations with the 11 year cycle and that plasma streams from higher latitudes might expand in such a way that they again cross the ecliptic plane somewhere beyond 1 AU.

On the other hand, as mentioned in section 2 gradient and curvature drift of cosmic rays in the regular large scale IMF pattern cause galactic cosmic ray particles to reach us through high latitude regions of the solar system. So it may still take some time, perhaps after exploration of regions off the ecliptic plane, until we know *where* most of the galactic cosmic ray modulation occurs and which solar parameters cause the necessary changes in interplanetary conditions.

A change in the galactic cosmic ray intensity as observed close to the earth must not necessarily be reflected in a large change of the *local* propagation conditions. On the other hand, the discussion in sections 2 and 3 suggests that the high degree of variability of propagation conditions for solar cosmic rays is at least partly ordered by the high-speed solar wind streams. If local interplanetary conditions are at times essentially scatter-free, this means that the time profile of a solar particle event is determined a) by solar injection processes, and b) by the location and reflection properties of a distant barrier or a diffusive shell.

The idea of a "diffusive shell" (see Meyer *et al.*, 1956) or of barriers for cosmic-ray penetration with varying location and extent has regained considerable attention. One such inference came from the so-called back-scatter method. Particle anisotropy measurements during solar events showed that in some cases it takes a very long time until the first particles are seen from the anti-solar direction (McCracken *et al.*, 1967). From the time delay between the source intensity from the solar direction and the back-scattered intensity one gets an estimate for the mean free path beyond the observer of the order of 1 AU or larger (see also Quenby *et al.*, 1974).

Independent information for >0.3 MeV solar protons has been obtained by Roelof and Krimigis (1973) from observations over extended time periods. They show that these protons have a behaviour very distinct from diffusive propagation. Most important is the observation that

> "Low-energy solar charged particles can exhibit field-aligned anisotropies in quasi-stationary (corotating) events, even during the zero-gradient exponential decay phase lasting several days of a flare-associated event"

(Roelof and Krimigis, 1973, p. 5376). The authors have introduced the concept of "collimated convection" to describe the particle behaviour. This is an idealized situation where the solar particles move scatter-free within the inner solar system out to the inner boundary x_0 of a scattering region, which keeps the particles from moving out immediately. In the scatter-free region, electric field drift causes the particles to stay along the same field-line. The negligible cross-diffusion means that particle populations can be traced back along the field to the high coronal injection longitude.

The theoretical explanation of a *field-aligned* anisotropy in case of a vanishing or small spatial gradient (which in the classical diffusion picture should lead to the *radial* convective anisotropy, see section 3.2) is given by Roelof (1973) and supplies rather convincing evidence for the propagation scheme suggested by Roelof and Krimigis (1973) for 0.3 MeV protons. It could not be obtained from a diffusion model with a small mean free path throughout the inner solar system. This means that under these propagation conditions any interpretation of an intensity-time profile by diffusion will lead to erroneous results; in this case the time profile in the onset phase and until beyond the maximum is largely determined by solar injection processes.

There is no reason why the "inner edge of the scattering region" should not move to within 1 AU at times; in this case one will see the convective effects related with the second and third phase of very long lasting solar events (Allum *et al.*, 1974). The fact that the anisotropy data also show low energy particle events where the anisotropy becomes very small shortly after onset (see McCracken *et al.*, 1967) clearly shows the existence of diffusive propagation; in these cases the mean free path derived from the time profile of the intensity agrees rather well with the "back-scatter" estimate of $\lambda_{\|}$.

There is an intermediate case, when the scattering in the inner solar system is small, but not totally negligible. Here neither the classical diffusion nor the idealized collimated convection model will adequately describe the propagation. Monte Carlo studies have been tried in this case (e.g. Palmer *et al.*, 1974), but it is clear that here details of the pitch angle scattering process are important, in particular since the scattering towards increasing pitch angle competes with the collimating effect of the diverging IMF (see Roelof, 1969).

This brings us to the final set of questions: What is the proper equation describing cosmic-ray propagation in (weakly or strongly) turbulent magnetic fields? How is the pitch angle diffusion coefficient obtained from magnetic field properties? Under which conditions can the resulting particle propagation be described by a spatial diffusion process, and how is the diffusion coefficient obtained?

It is not the purpose of this paper to review the theoretical attempts to improve and supplement the quasi-linear approach (see Klimas and Sandri, 1971; Völk, 1973; Fisk *et al.*, 1974, for details). But since the theory in its final form should allow to form the link between the two sets of observations (magnetic field fluctuations and cosmic-ray transport parameters) which we treated in this review, let us close with a series of remarks.

1. One of the prerequisites for the validity of the formalism introduced by Jokipii (1966) is the "weakness" of the interaction, i.e. the magnetic field fluctuations have to be small, in the sense that the variation in pitch angle during the time T_{gyr} of one gyration is small. This can be expressed by demanding that $\lambda_{\|}/v \approx T_{\text{rel}} \gg T_{\text{gyr}}$. As discussed by Wibberenz (1973) this condition is not fulfilled for protons around 100 MeV if the full spectral power according to Jokipii and Coleman (1968) is inserted. On the other hand, electrons in the MeV range and below are very good candidates for this condition to hold (see Lanzerotti *et al.*, 1973). The proton example shows the necessity to find more rigorous solutions of the pitch-angle scattering problem for *strong* turbulence, and not just corrections to the first order quasi-linear theory.

2. There seems to be general agreement (see e.g. Fisk *et al.*, 1974) that quasi-linear theory provides inadequate results for the pitch angle diffusion coefficient $D_\mu(\mu)$ at pitch angles close to 90° ($\mu = v_{\|}/v = \cos\varphi = 0$); one obtains for most types of fluctuations $D_\mu(\mu) \to 0$ for $\mu \to 0$ as long as $\mu \neq 0$. This singular behaviour as $\mu \to 0$ is removed if second order terms are taken

into account (see e.g. Völk, 1973, for the resonance broadening concept). Fisk *et al.* (1974) show that for a number of cases the difference between the exact numerical value and the quasi-linear approximation for D_μ amounts to a factor $|\mu|$ for $\mu \rightarrow 0$, but $\mu \neq 0$.

3. The spatial diffusion coefficient is obtained by a suitable averaging procedure over all pitch angles (see Jokipii, 1966; Hasselmann and Wibberenz, 1970; Earl, 1973). In the integral the smallness of D_μ for $|\mu| \rightarrow 0$ causes a divergence, which for not too steep power spectra is removed by second order corrections. However, the absolute size of $K_\parallel$ is very difficult to obtain because of the complicated nature of the mathematical expressions; this is reflected e.g. in the results by Völk *et al.* (1974). Under the assumption of the same form of the spectral tensor throughout space one can predict the radial variation of $K_\parallel$ with heliocentric distance and latitude, but its absolute value is only determined within an order of magnitude.

So it may still take some time until we get the final answer how the cosmic-ray transport parameters are to be determined from properties of the magnetic field. Should the preliminary indications be confirmed, namely that also in the final version of the theory the results depend strongly on the full spectral power in wave vector space, it might be difficult to get the answers from the presently available spacecraft measurements. Single spacecraft measurements just give the spectral power as a function of the radial component k_r of the full wave vector $\boldsymbol{k}$. We need more theoretical and experimental background on the true plasma-physical nature of the various IMF fluctuations. Therefore, it seems quite plausible that part of the answers will come from a continuation of cosmic-ray intensity and anisotropy measurements with good resolution in time, angle, and energy.

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