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Solar cosmic rays can gain access to the interplanetary magnetic fields near earth from flares located almost anywhere on the sun. There is evidence, for example, that flares located near central meridian on the invisible solar hemisphere can produce detectable increases in the intensity of ~ a few Mev protons at earth (Dodson, et al., 1968). Even with generous estimates for the extent of the random walk of interplanetary field lines (Jokipii and Parker, 1969), diffusion in the interplanetary medium can not account for these observations. There must exist, therefore, an efficient mechanism for the transport of cosmic rays in the solar corona. It is the purpose of this note to point out that the required transport may take place along current sheets separating discontinuous field structures in the corona. These sheets can serve as pathways along which energetic particles drift at nearly their propagation speed.

In Figure 1 we have shown the large-scale coronal magnetic field structure that has been calculated by Schatten (1971). Although some of the loops in the fields shown in Figure 1 connect areas on the sun separated by considerable distances, the majority are confined to connect areas no more than about 30^{o} apart, and certainly the field lines do not connect in all directions. The evidence from coronal field models is that there does not appear to be direct field line connection between all flare sites and the footpoint of the interplanetary field lines leading to earth (on the average at about 60^{o} west solar longitude, near the solar equator). Of course, one cannot rule out the possibility that there is a field structure in the corona not included in the coronal field models, that makes their predicted field topology inaccurate.

Note that for particles to travel considerable distances through the corona by following successively the field lines of separate loop structures, they must at each junction between loops return to low altitudes in the corona where the two loops are in close contact. However, such motion is improbable since particles should mirror before obtaining the required depth and ionization losses experienced by particles in the lower corona are substantial. Also, direct field line connection is required for the scattering of particles by, for example, hydromagnetic waves to have a dominant influence on the transport. The transport of particles across the mean field direction by scattering is an inefficient process, since a particle can be expected to move, at most, a distance of order one gyro-radius across the field with each scattering.

The corona exhibits filamentary structure on a scale down to the smallest dimension that can be resolved from earth (~ 4000 km) (Koutchmy and Laffineur, 1970). Associated with these observed coronal density gradients there may exist magnetic field gradients to support the pressure differences involved. The changes in the magnetic field can occur over quite small distances, and thus imply the existence of current sheets, similar to the "filamentary currents" suggested by Alfvén (1963). Energetic particles can drift along these current sheets with an efficiency that depends on the characteristic thickness of the sheets, ℓ. If ℓ is much greater than the particle gyro-radius, ρ, ($\rho \sim 10$ km for a 50 Mev proton in a 1 Gauss field), then the drift speed for non-relativistic particles is (Longmire, 1963):

$$v_D = \frac{cT_\perp}{eB^2} \hat{e}_B \times \nabla B$$

where $T_\perp$ is the kinetic energy in the motion of the particle perpendicular to the mean field direction $\hat{e}_B$, B is the magnetic field intensity, e, the electronic charge, and c, the speed of light. In this case, $v_D \sim v_\perp \rho/\ell$, where $v_\perp$ is the speed of the particle perpendicular to $\hat{e}_B$. On the other hand, if $\ell < \rho$ (Michel and Dessler, 1970)

$$v_D = v_\perp (B_2 \pm B_1) \sin \alpha / [\pi B_1 + \alpha (B_2 - B_1)]$$

where B_1 and B_2 are the field intensities on either side of the current sheet; these fields are assumed to be parallel (the - sign) or anti-parallel (the + sign). The angle α is defined in Figure 2 where the motion of a particle along a thin current sheet (where the fields on either side are anti-parallel) is shown schematically. In this case ($\ell < \rho$), v_D can approach $v_\perp$. In order to account for the efficient transport of energetic protons with energies greater than ~ 1 MeV, we require the existence of thin current sheets in the corona, not more than a few kilometers in thickness. Lower energy protons and electrons will of course propagate less efficiently by the mechanism. However, some of the lower energy particles seen at earth, particularly electrons with energies of a few times 10 keV, may not be accelerated in the original flare, but rather in connection with the flare-associated shock wave that propagates through the corona causing major disturbances (e.g. Athay and Moreton, 1961; Wild, 1969). Also, electrons may be stored in the corona and released into interplanetary space during flare-associated disturbances (Simnett, 1971). It may not be necessary, then, to transport low energy electrons and protons from the flare site to the footpoint of the interplanetary field leading to earth, unlike higher energy protons whose energetics require that they be the direct product of the original flare.

In Figure 3 we have shown schematically the propagation of a particle in the corona as it follows randomly oriented, thin current sheets. The transport of particles in such a configuration can be described by a diffusion process, with a diffusion coefficient $\kappa = \lambda V/3$. Here, λ is the characteristic length over which a particle follows a current sheet or series of sheets in any one direction, and $V = (v_{\parallel}^2 + v_D^2)^{1/2}$, where $v_{\parallel}$ is the speed of the particle parallel to the mean field. We refer to this diffusion process as "current sheet diffusion." Note that $v_D \propto T_{\perp}$ for $\ell \gg \rho$ and $v_D \propto T_{\perp}^{1/2}$ for $\ell < \rho$, on assuming that the particles are non-relativistic. The speed V, then, varies as T^{ν}, where T is the total kinetic energy of a particle and ν lies between 1/2 and 1, depending on the thickness of the current sheets and the particle pitch angle. Presumably ν is closer to 1/2 since we require thin current sheets.

Implicit in this diffusion picture is the requirement that paricles can follow current sheets over considerable distances. However, some fraction of the particles will be lost during the diffusion process by scattering from current sheets onto coronal fields that have smaller gradients. The storage of particles in the corona, which appears to occur during some flare events (Simnett, 1971) and is useful for explaining recurrence events (McDonald and Desai, 1970), could take place in these small gradient regions. It is also possible that diffusion occurs only in the lower corona (say, at an altitude less than a solar radius above the photosphere) where a greater variability in plasma density is observed (e.g. the extension of spicules up to the lower corona) and thus many current sheets are likely to occur. Storage may occur in the outer corona where the field gradients may be smaller and the ionization losses less. In fact, McCracken and Rao (1970) have noted that flare particles, which originate in the lower corona, diffuse further around the sun than do particles from delayed events, which apparently were stored in the outer corona.

Acceptable models for the transport of cosmic rays in the corona should account for the recent observations by McCracken, et al. (1971) that late in solar flare events the gradient in heliocentric longitude has an e-folding angle near 30° for ~10 MeV protons. Also, late in flare events the spectral index of the intensity spectrum, γ, is found to vary linearly with heliocentric longitude according to the relation

$$\gamma \simeq 4.2 - \psi/90° \tag{1}$$

where ψ is heliocentric longitude measured from the centroid of the distribution of cosmic rays in interplanetary space (McCracken, et al., 1971). Of course, it is difficult to separate effects due to diffusion in the corona from those due to diffusion, convection, and energy loss in interplanetary space.

Suppose that cosmic ray particles are emitted impulsively from a flare, and then undergo current sheet diffusion along a layer at a distance r from the heliocenter. For simplicity, suppose that this diffusion can be considered to be one-dimensional in the variable $r\psi$ (ψ in the corona is the projection of ψ in the interplanetary medium back along the spiral interplanetary field). The integral we will perform is much simpler with the assumption of one-dimensional diffusion and yet the results are essentially the same as in the more realistic two or three dimensional models. This one dimensional model may not be too unrealistic if following the flare, particles propagate freely onto the fields of a single, large-scale loop structure in the corona, and then diffuse perpendicular to this loop via current sheet diffusion.

Suppose also that the characteristic time for particles to leak into the interplanetary medium is τ. (We neglect the possibility that particles can be trapped in the corona and not leak into the interplanetary medium.) This time τ, as well as the characteristic time for coronal diffusion, should be short compared with the time scale for diffusion and convection in interplanetary space. (This may not be true of electrons; see a brief discussion of this by Fisk and Van Hollebeke, 1971.) Consequently, almost all of the flare particles will have leaked into the interplanetary medium before the intensity seen at 1 AU begins to decay with time. At late times t, following the flare, the differential intensity at 1 AU is then essentially the same as the intensity that would result from the impulsive release at t = 0 of

$$N(r,\psi,T) = N_o(T) \int_o^\infty \frac{\exp\left(-\frac{r^2\psi^2}{4\kappa t} - \frac{t}{\tau}\right)}{\tau\sqrt{\pi\kappa t}}\, dt$$
$$= \frac{N_o(T)}{\sqrt{\tau\kappa}} \exp\left(\frac{-r\,\psi}{\sqrt{\tau\kappa}}\right) \qquad (2)$$

particles, per unit area, through the surface at r. Here $N_o(T)$ is the differential spectrum of particles injected by the flare (per unit length since the coronal diffusion is one-dimensional).

The variation of N with ψ can easily account for the e-folding angle $\sim 30^o$ (0.5 radians) measured for the azimuthal gradients of $\sim$ 10 MeV protons (McCracken, et al., 1971). If we choose $r = 1.5$ solar radii, $\tau = 15$ minutes, then the required $\kappa = 3x10^{18}$ cm^2/sec. If we assume that $\sim$ 10 MeV protons drift along the coronal current sheets with a speed $V \sim 3x10^9$ cm/sec (the propagation speed of a 10 Mev proton is $6x10^9$ cm/sec), then the characteristic length that a particle moves in any one direction is $\lambda \sim 3x10^4$ km. This value for λ, which is a measure of the scale over which the current sheets or coronal fields are ordered, is roughly the projection into the corona of the characteristic dimension for supergranular cells in the photosphere. With these values for κ and r, an $\sim$ 10 MeV proton can diffuse half way around the sun ($\psi = 180^o$) in a time $\sim r^2 \psi^2 / 2\kappa$ = 5 hours, which should be sufficiently rapid diffusion to account for most flare observations.

Because cosmic rays lose energy in the expanding solar wind the rate of decay of the intensity with time in the interplanetary medium depends on the spectral index γ, increasing with increasing γ (Fisk and Axford, 1968; Ng and Gleeson, 1971; Forman, 1971). Thus from (1), the intensity near the centroid of the cosmic ray distribution in the interplanetary medium will decay more rapidly than the intensity at larger values of ψ. This effect, as well as diffusion transverse to the mean field, will reduce the azimuthal gradient in the interplanetary medium, or equivalently a 30° e-folding angle at 1 AU implies a smaller e-folding angle at the Sun. Thus, our estimates of κ and/or τ may be too large; however, they are unlikely to be significantly in error.

The argument of the exponential in (2) varies relatively slowly with energy, as $T^{-\upsilon/2}$, $1/2 \leq \upsilon \leq 1$, on assuming that τ and λ are undependent of energy. With κ and τ adjusted to agree with the above values for ~ 10 MeV protons, an injection spectrum that is a power law in kinetic energy, $N_o(T) \propto T^{-\mu}$, will bend over only gradually toward low energies (down to a few MeV). A power law spectrum will be preserved in the interplanetary medium at late times, provided that the interplanetary diffusion coefficient is not a strong function of energy and/or the late time decay is determined principally by convection and energy loss effects (e.g. Forman, 1971). Thus, at late times an injection spectrum of the form $N_o \propto T^{-\mu}$ may produce a spectral index for the intensity in interplanetary space that is essentially

$$\gamma = -\frac{j}{T} \frac{\partial j}{\partial T} = \left(\mu - \frac{\nu}{2} - \frac{1}{2}\right) - \frac{\nu}{2} \frac{r \psi}{\sqrt{(\tau\kappa)}} \tag{3}$$

where j is diferential intensity and the extra value of 1/2 enters because intensity is proportional to particle velocity ($\propto T^{1/2}$) times number density. With $\mu \sim 5$ and $r/\sqrt{(\tau\kappa)} \sim 1/30^{\circ}$ for ~10 MeV protons, (3) agrees quite well with (1).

In conclusion, we have suggested in this note that the transport of cosmic rays in the corona may take place along thin current sheets. It is important to realize, however, that we do not have sufficient observations to construct a definitive model for coronal transport, and that models other than the one presented here are certainly possible.

Acknowledgment

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Figure Captions

Figure 1 - The coronal magnetic field calculated by Schatten (1971) for the Nov. 12, 1966 solar eclipse using the "current sheet" model. The dashed circle at 1.6 solar radii is the location, in this model, where current sheets in the solar wind form. The coronal magnetic field is projected into the plane of the sky. Note that although a considerable looping of the magnetic field occurs, it does not appear possible to connect field lines from most locations on the sun to 60° west longitude.

Figure 2 - Schematic showing the motion of an energetic particle on a thin "current sheet." The particle's motion parallel to the field is unaffected; the motion perpendicular to the field is converted into a net motion along the surface of the current sheet.

Figure 3 - The diffusion of an energetic particle along a series of current sheets in the corona. The corona may be separated into a filamentary field structure perhaps arising from the extension of the granulation and supergranulation. Energetic particles could diffuse, as shown, along current sheets associated with these structures.

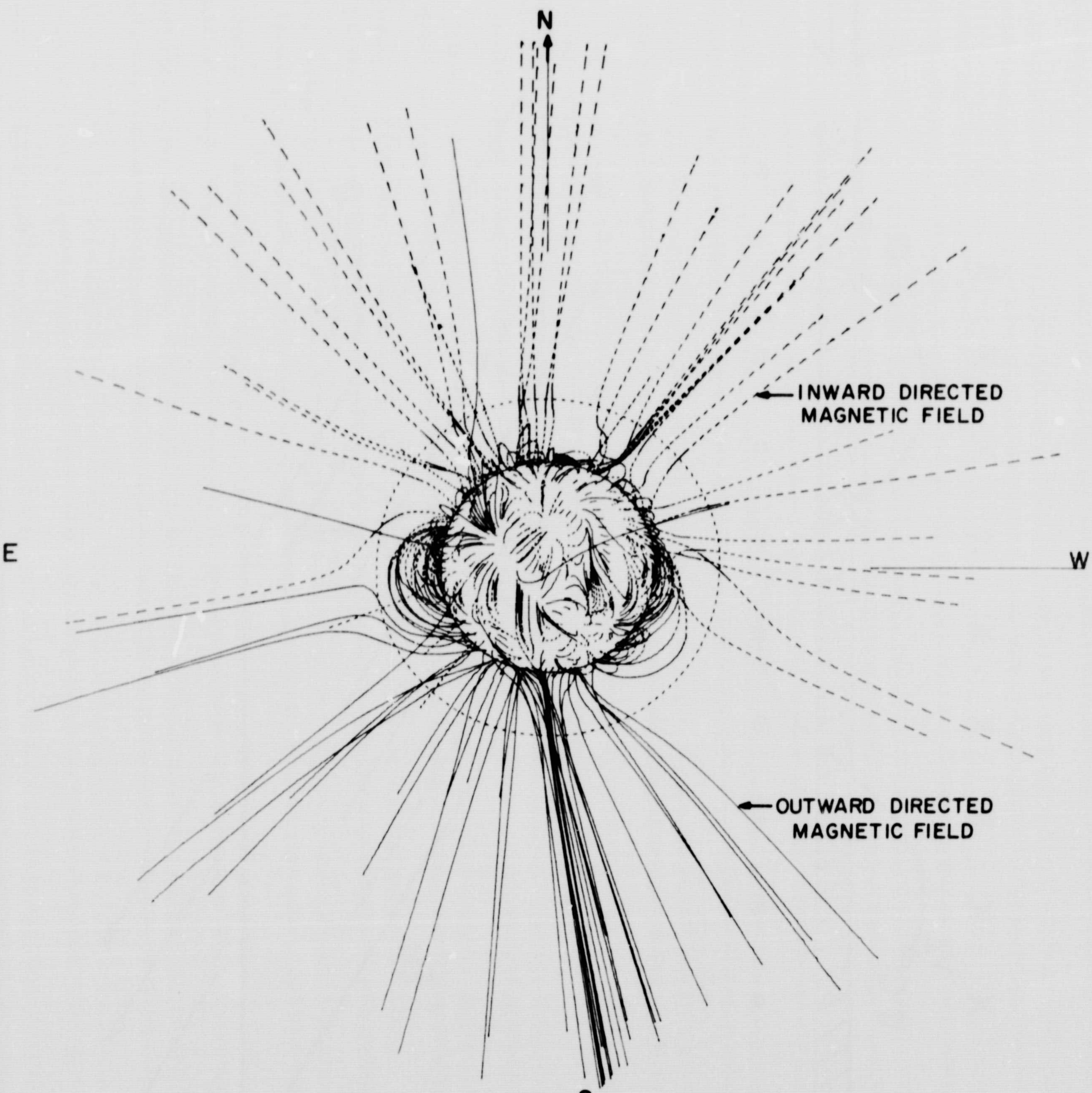
N
E
W
S
INWARD DIRECTED
MAGNETIC FIELD
OUTWARD DIRECTED
MAGNETIC FIELD

FIGURE 1

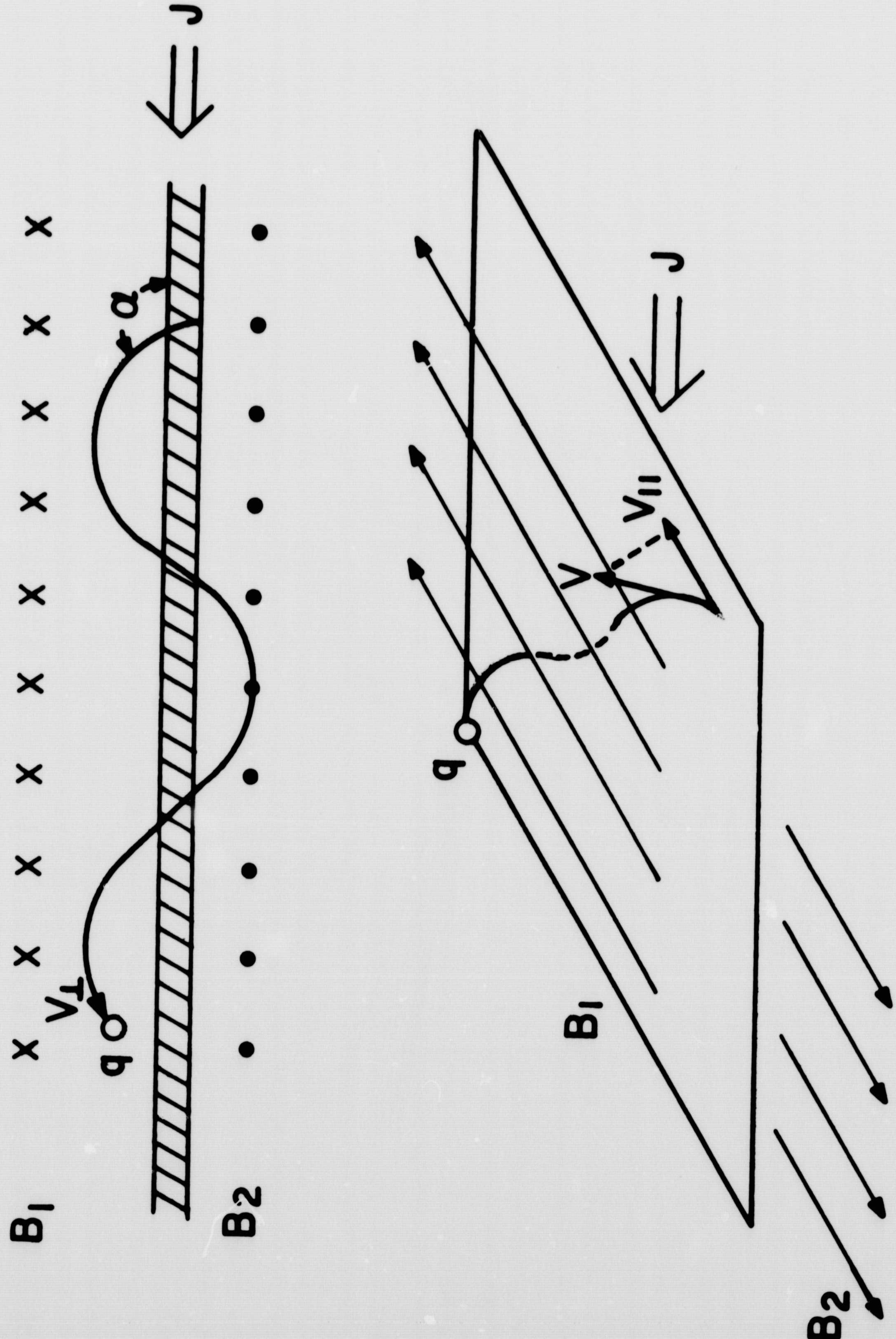

FIGURE 2

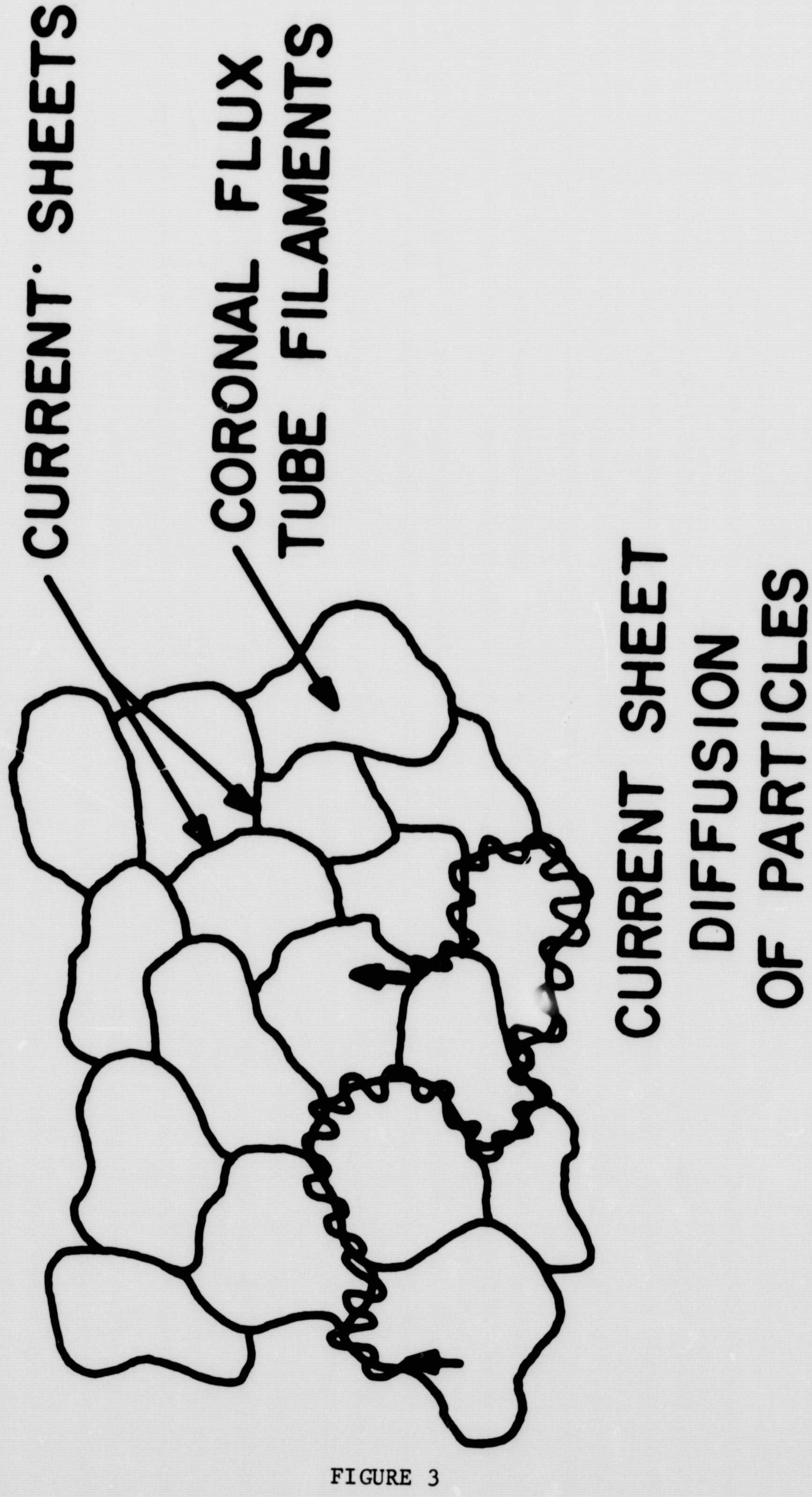
CURRENT SHEETS
CORONAL FLUX TUBE FILAMENTS
CURRENT SHEET DIFFUSION OF PARTICLES

FIGURE 3