MOTION OF SOLAR COSMIC RAYS IN THE CORONAL MAGNETIC FIELD

D. J. MULLAN and K. H. SCHATTEN*

Bartol Research Foundation of the The Franklin Institute, University of Delaware, Newark, Del. 19711, U.S.A.

(Received 21 April; in revised form 9 October, 1978)

Abstract. Trajectories of solar cosmic rays have been calculated in a static ninth-order coronal magnetic field. It is found that as a result of field curvature and gradients, protons drift across the field lines at a rate of up to $200 \gamma b^2 \text{deg hr}^{-1}$. These drift rates are of the same order as, but somewhat smaller than, empirically derived rates. Localized enhancements of magnetic field have been inserted into the ninth-order field in order to model (in a highly idealized manner) the effects of the small-scale magnetic features which give rise to X-ray bright points. The motions of the particles in the presence of these scattering centers can be parameterized approximately by a cross-field diffusion coefficient. Our estimates of this coefficient, although crude, overlap with empirical values which have been deduced over a wide range of energies.

We propose that coronal propagation of solar cosmic rays has two components. One is independent of particle velocity, and is associated with dynamic field phenomena (such as an expanding magnetic bottle): this is the only component which is important in flares which occur close to the foot-point of the Sun–Earth field line. The second component is velocity dependent, but is independent of mass, and is associated with scattering off (relatively static) magnetic inhomogeneities with scale sizes of at least 500 km: the second component contributes to coronal propagation if the flare occurs more than about 50–60 deg away from the Sun–Earth field line.

1. Introduction

Solar cosmic rays are known to approach the Earth anisotropically along the Archimedean spiral field line. This Sun–Earth field line (SEFL) is connected to the Sun at a longitude of approximately 60° W, and at a latitude which is closer to the equator than ±7°. Even if a flare site lies far from the SEFL, particles from the flare can nevertheless be injected onto the SEFL within a short time after the flare. As an example, Figure 1 shows the locations of flares which produced ground level events (GLE) shortly after the flare: the broad distribution over the solar surface is striking. The occurrence of significant anisotropy in the particle fluxes detected at the orbit of the Earth indicates that the azimuthal propagation of the particles is controlled by processes occurring close to the Sun, rather than in interplanetary space (Wibberenz, 1976). These processes form part of a chain of effects which occur during the time interval between acceleration and detection. The data must be compensated for these effects before it will be possible to unravel the physics of solar particle acceleration (Roelof and Krimigis, 1977). The purpose of this paper is to discuss one particular near-Sun process: we compute trajectories of solar cosmic rays as they

* Current address: Institute for Plasma Research, Stanford University.

Copyright © 1979 by D. Reidel Publishing Co., Dordrecht, Holland, and Boston, U.S.A.
propagate through the corona, and in the calculations we adopt strictly static magnetic fields which are as realistic as is computationally feasible. However, it is not the aim of this work to discuss the trajectories of particles as they escape from the Sun, although this process is also controlled to a significant extent by static field structures (Roelof et al., 1978).

In a previous paper (Schatten and Mullan, 1977), we discussed one component of the particle propagation in the corona. We suggested that a proton flare would produce dynamic distortions in the local solar magnetic field, forming an expanding magnetic bottle. It was shown that bottle expansion would proceed to a distance of order 60° from the flare site in a time scale of less than one hour, after which Rayleigh–Taylor instability would cause the bottle to break open. Particles escaping directly from the open bottle would constitute the prompt component of solar cosmic rays. It is now known that mass ejection from the Sun is indeed a necessary condition for producing prompt particles at the Earth (Kahler et al., 1978): this is consistent with the bottle model. Other aspects of agreement between the model and observations are summarized by Schatten and Mullan. It should be noted that direct evidence for flare-induced opening of coronal field lines is usually available only for the most violent flares (Newkirk, 1975): the bottle model envisages that flare-induced field line opening occurs in all flares which produce prompt proton events at Earth.

Fig. 1. Plot of all flares producing GLE. The center of this diagram (termed a Copernican diagram by Duggal and Pomerantz (1973)) is the meridian passing through the footpoint of the nominal garden hose field line that connects the Sun to the Earth. Invisible disk events are circled. The centroid is indicated by an asterisk.