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TWO VIEWS OF COSMIC RAY PROPAGATION IN THE SOLAR SYSTEM

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It has long been established that the cosmic rays falling into the solar system are very steady both in intensity and in direction, and that their variations or anisotropies as measured at earth or by satellite borne detectors are caused by factors within the solar system.

The main variations observed are the 11-year modulation of intensity, which is closely associated with solar cycle, the diurnal variation, which is understood as the detection of a streaming of the cosmic rays by detectors rotating with the earth, Forbush decreases, which are sharp decreases sometimes associated with very noticeable solar and geomagnetic disturbances, and solar flare increases.

Over the years, the consensus among workers in this field has taken shape in a theory ascribing these variations to propagation properties of cosmic rays in the solar system,

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which can briefly be summarised as follows: The cosmic rays interact with irregularities in the magnetic field associated with the solar wind. These irregularities are very numerous, and each elementary interaction produces a small deflection of the particle's trajectory. In the primitive form of the theory, this process was assimilated to a diffusion process like sugar dissolving in tea, the mathematical formulation of which was well known, and, with appropriate modifications due to the different geometry and conditions at the boundaries this theory in various forms met with good success in interpreting a number of phenomena, especially the shape of the time-intensity profiles of solar cosmic ray events at high energies and the diurnal variation of cosmic rays. At the time, the eleven-year modulation was also qualitatively explained by a supposed variation in the number of scattering centers associated with the solar cycle. Since these centers are attached to the solar wind which is flowing away from the sun, there is a net reduction of the cosmic ray intensity as one goes nearer to the sun, and this reduction would vary with the variation in the number of scattering centers.

With the advent of accurate measurements of the interplanetary magnetic field by satellite observations it became possible to relate the observed magnetic properties to the cosmic ray observations. This was done in a very elegent mathematical analysis by Jokipii in a series of papers where, in the framework of this picture of multiple small-angle scattering by numerous irregularities the observed statistical properties of the interplanetary magnetic field (which was assumed to satisfy certain mathematical constraints of homogeneity in the amount of randomness, etc.) were related to quantities such as the diffusion coefficient which could be derived from the observed values of the diurnal variation, or the shape of the time-intensity profiles of solar proton events.

At the same time, numerous workers (Fisk, Gleason, Axford, Forman and others) were working out the detailed implications of the theory concerning related aspects of cosmic ray observations, resolving discrepancies in the theoretical fit to the observations, predicting new properties to be observed at different energies with definite success at every step. This theory has become part and parcel of all thinking on cosmic ray phenomena.

During the past four or five years an alternative viewpoint has been occasionally suggested which is in total disagreement with this theoretical scheme. In this alternative the cosmic rays do not experience interactions with numerous scattering centers, nor are these interactions small-angle interactions: on the contrary, a relatively small number of scattering centers are assumed, each interaction may cause arbitrarily large directional changes, and the particle motion is supposed to be scatter free in the average interplanetary magnetic field for long periods between interactions. The interplanetary magnetic field serves principally to guide the motion of the center of gyration of the individual particles along the field lines. The idea is rarely stated as baldly as it is here, since people are aware of the many successes of the current theory, and some small angle scattering or rather, some diffusive behavior, is obviously necessary to account for certain aspects of the observed phenomena. However, a clear statement of the alternative viewpoints is required to explore the differences between the two extremes.

It is worthwhile to state the stages in which this second viewpoint come to be crystallised. With respect to solar cosmic rays, Reid (1964) had suggested that the diffusion took place only at the solar surface with the particles leaking out and filling the interplanetary medium between the sun and some distant boundary. McCracken, studying the time dependence of the anisotropy in certain solar events at moderate energies, had come to the conclusion that a mean free path larger than 0.5 astronomical units was necessary to account for the observations, in contrast with 0.01 astronomical units accepted by the diffusion-type theories. Krimigis had suggested that at low energies the shape of the time intensity profiles was better accounted for by assuming continuous ejection of particles from the sun than by diffusion of an instantaneously ejected burst of particles. This idea has been refined by Roelof and co-workers into a detailed correspondence between the observed profiles and observed features on the sun, incorporating the notion of storage within well defined regions on the sun. Barouch had shown that time-intensity profiles very similar to the observed profiles may be calculated on the assumption of adiabatic motion and a single scattering center. Klimas and Sandri, and Jones and co-workers have criticized the mathematical foundation of the latest version of the diffusion theory, claiming that it breaks down for certain energy ranges, as has Roelof, from a different point of view.

More cogently still, new evidence has been obtained from recent work casting doubt on certain predictions of the theory. Many workers have observed that the statistical properties of the interplanetary magnetic field do not change appreciably over the solar cycle. To explain the eleven year modulation under these conditions the diffusion-theorists have had to resort to arguments concerning a variation in size of the modulation region for no easily explicable reason, or to ascribe the modulation to that region of interplanetary space which has not been explored by satellite.

Another prediction of the diffusion type theories was a large solar radial gradient of the cosmic ray intensity, with certain predictions concerning the behavior of different chemical species present in the cosmic radiations.

The determination of the radial gradient by the Pioneer 10 experimenters is in direct contradication to the theoretical predictions in both respects (McDonald et, al,Simpson et al.,Van Allen et al), in agreement with an earlier measurement by Krimigis.

To examine the quality of the alternative viewpoint, hypothetical models of conditions in interplanetary space which would give rise to the proposed behavior must be proposed and their consequences examined. One model which seems to have certain attractive features is described in the following lines.

Either through the direct effect of solar activity, or by dynamical interactions between different streams in the solar wind, blobs of very highly magnetised material are created infrequently in interplanetary space in an otherwise approximately smooth, spiral, magnetic field. These blobs move outward from the sun till they reach the boundary of the heliosphere, where they are confined till their identity is destroyed by field merging or other processes.

Cosmic ray particles, whether solar or galactic, traverse the solar system (between encounters with blobs) in adiabatic motion, gyrating about centers constrained to move along the field lines, with little or no scattering. On meeting a blob, their directions are changed drastically, as are their pitch angles, they may even mirror at the blob and start moving in the other direction. All particles will mirror close to the sun, where presumably the high, irregular, magnetic field always present will cause considerable changes in the orbital parameters, ensuring a further isotropisation of cosmic ray density.

Now consider the evolution of a blob created by a stream-stream interaction. It is created at some distance from the sun, several tenths of an A.U., initially as a small field enhanced region whichis then carried outwards by the solar wind. During the lifetime of the fast stream the blob increases in size and in field strength. Because it is evolving and moving outwards, a wake of reduced cosmic ray intensity is created in the region behind the blob. When the high velocity stream subsides the sunward extremity of the blob tapers off to the normal interplanetary parameters and as the blob moves outwards it also probably tends to return to the average values. However this appears to be a much slower process, so that these blobs have a semi-permanent character in space.

Behind the blob we thus have a depletion region of cosmic rays which fills in gradually either through particles traversing the blob or through residual scattering processes. The extent of the depletion depends on the particular epoch in the life-time of the blob, on the proximity of other similar blobs and on the intensity and dimensions of the enhanced magnetic field.

By chosing appropriate values for the average dimensions and separation of these blobs, the observed diurnal variation and the time-intensity profiles of solar proton events can perhaps be accounted for. If one further assumes that the number and/or quality of these blobs varies with the solar cycle, then the eleven-year modulation may be qualitatively explained as well.

In support of this model one can present the actual plot of the intensity of the interplanetary magnetic field over a long period. This figure (Fig. 1) was prepared for an investigation of the Forbush decrease phenomenon, and one can in fact see the close association between the high intensity magnetic fields and the Forbush decreases in the cosmic ray intensity. For the purpose of this paper, it suffices to observe that infrequent isolated regions of very intense magnetic field do in fact seem to be a feature of interplanetary space. Fig. 2 shows the association of these regions with high velocity streams. Whether the influence of these blobs on cosmic ray propagation is in agreement with the proposed model, and whether neglecting the influence of the field fluctuations between the blobs is justifiable, is still under investigation.

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One can make up a table comparing the two viewpoints.

Diffusion	Scatter Free
Well developed mathematical theory covering all aspects	Theory undeveloped as yet.
Explain isotropic events very well	Has difficulty in explaining isotropic events.
Can explain anisotropic events only if anisotropy $< 30\%$	Best for highly anisotropic events
Difficulty in explaining the low radial gradient	Low gradient inherent in view point till very large radial distances
Difficulty in explaining eleven year modulation	Unchecked but in principle hopeful
Inapplicable to Forbush decreases	Forbush decreases explained naturally by theory

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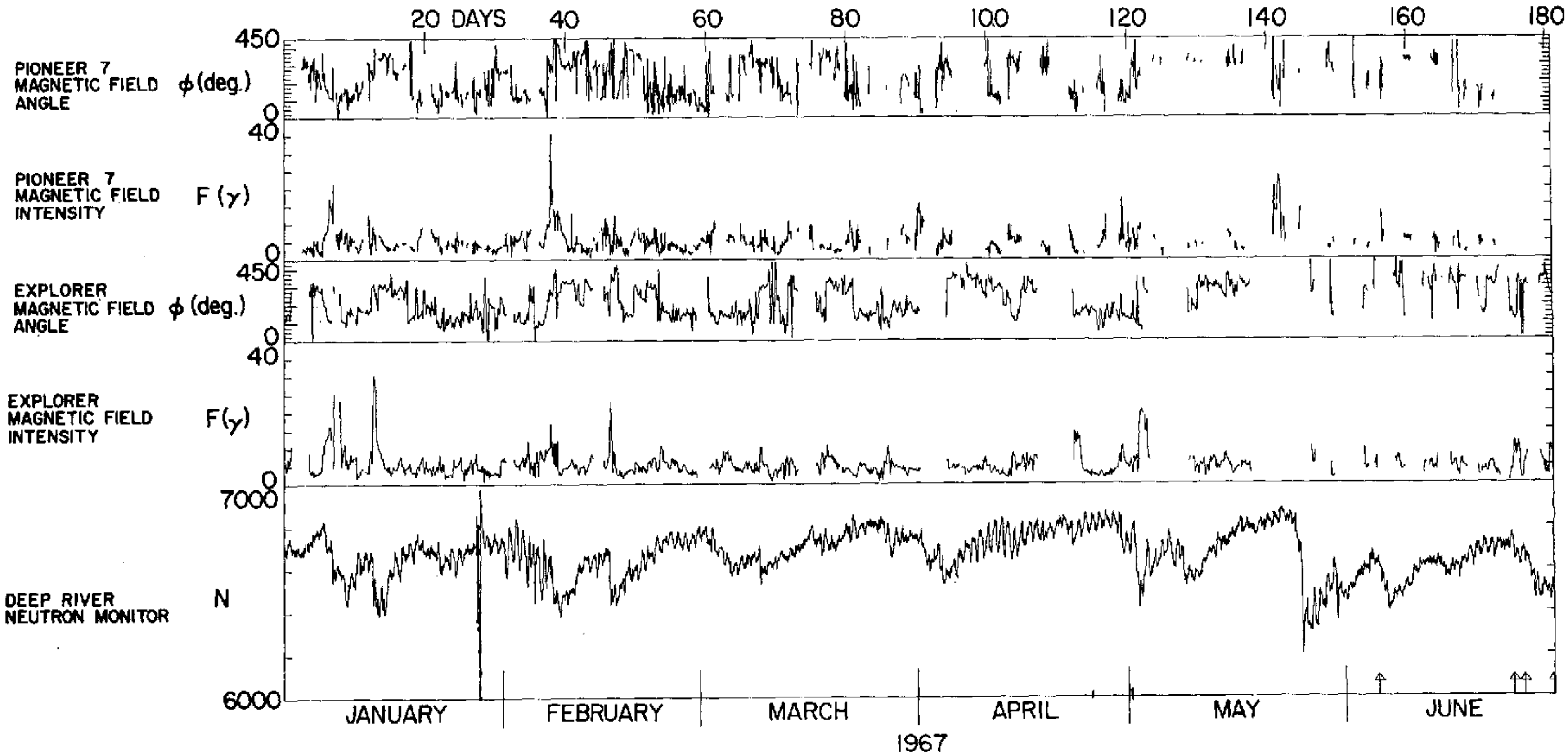

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PIONEER 7 MAGNETIC FIELD ANGLE
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PIONEER 7 MAGNETIC FIELD INTENSITY
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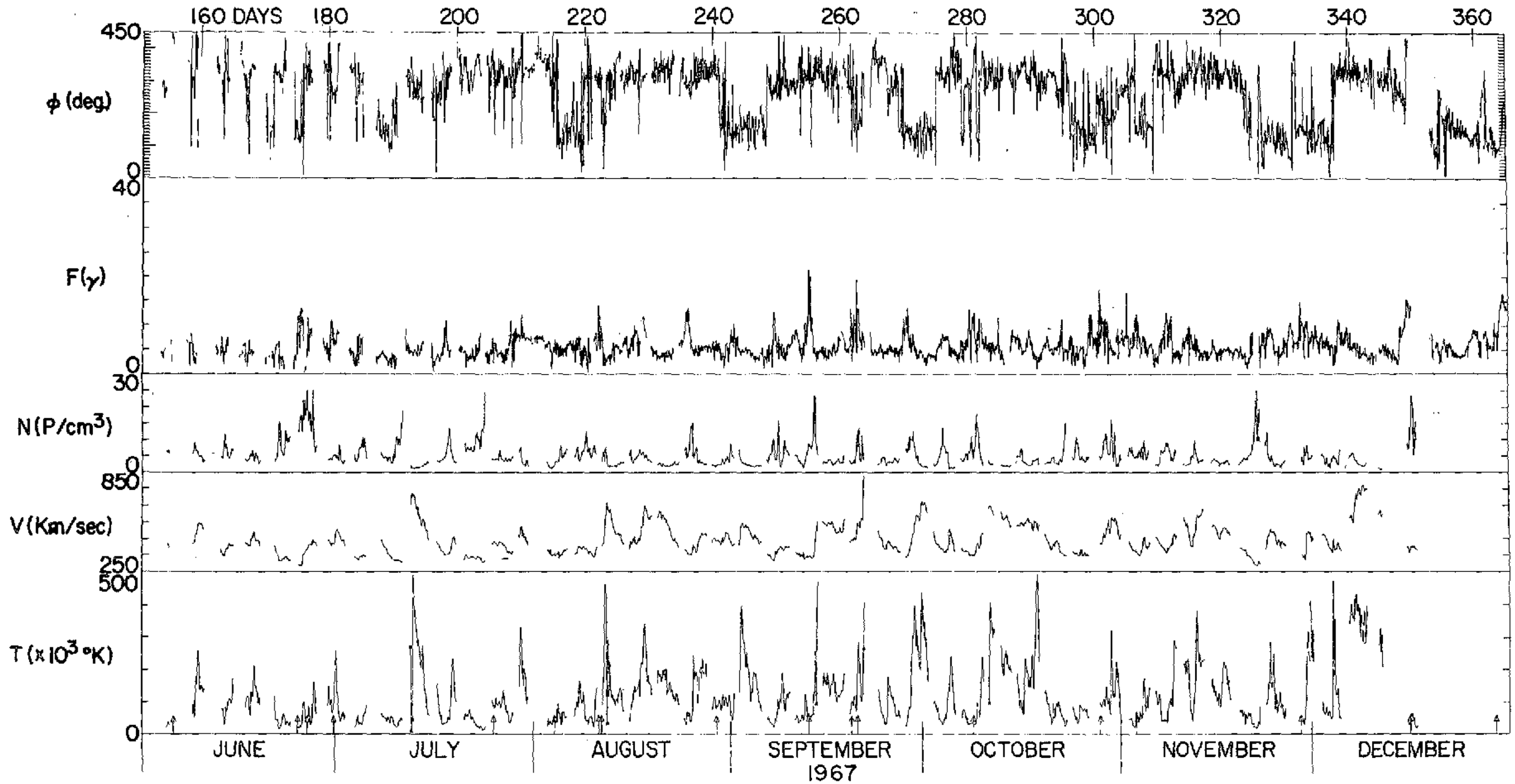
1967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JUNE
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DECEMBER

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