Final Report

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Study of the Modulatory Effects of the Solar Wind on Galactic Cosmic Rays

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Introduction

The modulatory effects of the solar wind on galactic cosmic rays as they are transported through the solar system has been a subject of investigation by several authors. The usual approach to the problem is to choose a model, write the appropriate transport equation, and solve it by making some type of diffusion approximation. Our approach is to solve the transport problem using Monte Carlo techniques, thereby avoiding diffusion approximations and the difficulties with estimating diffusion coefficients parallel and perpendicular to the magnetic field.

Through this analysis we obtain the cosmic ray flux and energy spectrum at any desired point in the solar system as a function of the incident galactic cosmic ray spectrum. These data then show directly the modulatory effects of the solar wind and in particular indicate whether the cosmic ray spectrum is hardened or softened by the action of the wind. Integrations with respect to energy over the spectra obtained allows us to determine the energy balance between the cosmic rays and the wind at any desired point inside the solar system as well as the overall direction of energy flow.

We have constructed a Monte Carlo analysis of the cosmic ray transport problem using the essential features of solar wind model proposed by Parker[1] which experimental evidence seems to support. The model in its simplest form consists of a spherically symmetric steady uniform wind extending from the sun to distances of the order of 20-100 A.U. (astronomical units). On this picture turbulence of a random nature is imposed. Since the magnetic lines of force are carried with the solar wind, the resulting magnetic field seen by a charged particle is a relatively steady radial field with random fluctuations superposed on it. These fluctuations are assumed to move outward with the speed of the wind since the Alven velocity is small compared to the wind velocity. A charged particle moving through the field may then be scattered by the turbulence and/or reflected by the steady field. Mirroring by the steady field takes place, of course, only for incoming particles while particles moving in either direction may be scattered. From the viewpoint of a fixed reference frame, the presence of the steady field does not change the energy of the charged particles while a scattering event may result in a net loss or gain of energy. The Monte Carlo analysis consists of following individual particles by keeping track of their momentum and position as they enter the sphere of influence of the solar wind and move about in this region. The Monte Carlo program has been coded, checked-out, and is now completely operational.

Magnetic Scattering

Our studies of magnetic scattering by small field irregularities as well as random walk of the field lines themselves indicate that the scattering mean free path is proportional to the wavelength of the disturbance. If the wavelength is the order of the radius of gyration of the particle, the particle may then be scattered isotropically in the rest frame of the solar wind. Measurements made by the Mariner 4 spacecraft of the power spectrum of the magnetic field give us an indication of the frequency and scale of magnetic fluxuations from 29 Nov. to 30 Dec., 1964. These data indicate that

$$P(f) \propto f^{-3/2}$$

where $P(f)$ = the magnetic power density

f = frequency of the fluxuations

Then if we require $\lambda \gtrsim R$

where λ = wavelength of the disturbance

R = radius of gyration of the particle as the condition for scattering, and let P(f) be a measure of the scattering mean free path. Then

$$L(f) \propto P(f)$$

where L(f) refers to L for a particle whose radius of gyration is of the order of λ ($\lambda = \frac{V}{f}$) and V is the velocity of the solar wind. Let L(p) denote the mean free path of a particle of momentum p, then $L(f) \propto \frac{1}{f^{3/2}}$, and since $\lambda \gtrsim R$,

then $\lambda \propto r^2 p$ where r = distance from the sun

p = momentum of particle.

and $L(p) \propto \frac{1}{\frac{V}{r^2 p^{3/2}}}$ or $L(p) \propto (r^2 p)^{3/2}$ for V constant.

This relation is then valid for r = 1 A.U. since the Mariner 4 data was obtained in this vicinity. If we assume that the magnetic turbulence increases linearly with r, then

$$L(p,r) \propto \frac{(r^2 p)^{3/2}}{r} = r^2 p^{3/2}$$ for all values of r. By similar arguments if we assume that P(f) approaches a constant value as f approaches zero (random walk of the field lines) then $L(r,p) \propto r^2 p$- for large values of p.

Monte Carlo Results

The scattering mean free paths as discussed above were incorporated into our analysis and the scattering probabilities determined from these data. We took the following values for the paremeters used in the program:

L(r,p) = .1 A.U. for r = 1 A.U. and p = 1 Bev./c, and r_m = 21 A.U. were r_m = radius of influence of solar wind, and V = 300 km/sec. where V = velocity of the solar wind. We sampled our incident particles from an energy spectrum of the form $\psi(E) \propto E^{-1.5}$ where $\psi(E)$ is the total number of particles with energy greater than E. The Monte Carlo analysis then gave us the energy spectrum and relative number of particles at our detector points. We placed one detector at 1 A.U. from the sun and the other at 20 A.U.'s. The results of calculation performed to date can be summarized as follows:

E_{in} is very nearly equal to E_{out} at both detectors where E_{in} is the energy flux toward the sun and E_{out} is the energy flux away from the sun.

At the 1 A.U. detector (dectector number 1) $\frac{\phi_1}{\phi} = .3$

in the 1 Bev./c to 10 Bev./c momentun range of incident particles

where ϕ_1 = particle flux at detector 1

ϕ = incident particle flux at 21 A.U.

At the 20 A.U. detector (detector number 2) $\frac{\phi_2}{\phi} = 1.3$

where ϕ_2 = particle flux at detector 2.

Examination of these results leads to two pertinent conclusions: (1) the solar wind does not substantially change the energy of the cosmic rays and (2) low energy particle intensity in the vicinity of the earth is considerably reduced from its galactic value. As we accumulate more Monte Carlo data, more detailed analysis of the modulatory effects of the solar wind on galactic cosmic rays will be possible.

References

1. E. N. Parker, Astrophy. J. 128, 664 (1958)