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MONTE CARLO CALCULATIONS OF RELATIVISTIC SOLAR PROTON PROPAGATION IN INTERPLANETARY SPACE

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ABSTRACT

Particle fluxes and pitch angle distributions of relativistic solar protons at 1 AU have been determined by Monte Carlo calculations. The analysis covers two hours after the release of the particles from the Sun and total of $8 \cdot 10^6$ particle trajectories were simulated. The pitch angle scattering was assumed to be isotropic and the scattering mean free path was varied from 0.1 to 4 AU.

As an application, the solar injection time and interplanetary scattering mean free path of particles that gave rise to the GLE on May 7, 1978 were determined. Assuming exponential form, the injection decay time was found to be about 11 minutes. The m.f.p. of pitch angle scattering during the event was about 1 AU.

1. INTRODUCTION

When a relativistic charged particle is injected into the interplanetary space from the Sun it becomes under the influence of the interplanetary magnetic field (IMF). Due to the divergence of the IMF, the pitch angle, α, of the particle decreases and the propagation becomes almost field-aligned. The nominal IMF is disturbed by small-scale irregularities, which act as scattering centers of the particles during their propagation. In these scattering processes the energy of the particle is conserved and the displacement of the guiding center is only of order of the gyroradius but the pitch angle of the particle changes.

When the scattering m.f.p., λ, is very small compared with the scale lenght of the IMF, the propagation is dominantly stochastic and the particle flux density can be described by a diffusion equation. But when λ increases, the deterministic role of the focusing magnetic field becomes more important. During highly anisotropic events a general description of the interplanetary propagation of relativistic solar particles is possible only by using the Monte Carlo method.

Lockwood et al. (1982) have applied the particle distributions calculated by Monte Carlo method in an analysis of the GLE on May 7, 1978. They found an average scattering m.f.p. of 5 AU during this event.

2. PARTICLE PROPAGATION IN THE IMF

2.1. Magnetic Focusing. In this work we have approximated the interplanetary magnetic field by the classical Archimedean spiral field. The angular velocity of the Sun was $2.865 \cdot 10^{-6}$ rad/s and the solar wind speed was 450 km/s, which is slightly above its average quiet time value.

The conservation of both the magnetic moment and the momentum of a particle during its propagation in a magnetic field of strength B, states that $\sin^2\alpha/B$ remains constant.

2.2. Pitch Angle Scattering. The scattering of a particle from magnetic irregularities depends, in addition to the rigidity of the particle, also on the strength and structure of the scattering centers. If the distribution is forward with respect to the direction of motion before scattering, there is less back-scattering and consequently the total particle flux decreases faster, than if the scattering were isotropic. In this work we chose the pitch angle scattering to be isotropic.

2.3. The Monte Carlo Method. The particles were injected isotropically from the solar corona at a distance of 0.02 AU from the center of the Sun. The distance to the first scattering along the field line was taken to be $\Delta s = -\lambda \ln x$, where x is a random number evenly distributed between 0 and 1. After the scattering, a new pitch angle was given by $\alpha = \arc\cos(1 - 2x)$, where x is a new random number. Then the distance Δs to the next scattering center was determined as above. During two hours after the injection, the time elapsed and the pitch angle were recorded every time the particle passed 1 AU in either direction.

The number of trajectories calculated in this analysis varied from $5\cdot10^5$ (λ=0.1 AU) to $2\cdot10^6$ (λ=4 AU).

2.4. Anisotropy. Let us denote by $F(\alpha)$ the pitch angle distribution and by $I(\alpha_0)$ the average density of particles having the pitch angle $\alpha \leq \alpha_0$, and by $I(\overline{\alpha_0})$ the average density for $\alpha > \alpha_0$. The anisotropy of the solar particle flux is conventionally defined by either

$$A = \frac{F(0^\circ) - F(180^\circ)}{F(0^\circ) + F(180^\circ)} \quad \text{or} \quad A = \frac{I(90^\circ) - I(\overline{90^\circ})}{I(90^\circ) + I(\overline{90^\circ})}$$

During solar particle events, the detectors at Earth, having their asymptotic directions of approach near the IMF field line, receive the majority of solar particles from a very narrow but finite cone. Therefore, we defined the anisotropy between two stations as

$$A = \frac{I_1 - I_2}{I_1 + I_2}$$

where I_1 and I_2 are the average particle densities in the asymptotic cones to which the stations 1 and 2 mainly respond.

3. RESULTS AND DISCUSSION

3.1. Intensity at 1 AU. The intensity-time profiles of particles at 1 AU after a delta-like injection are shown in Figure 1. The particles arriving during the first minute are, in addition to the unscattered particles, also those which are scattered either near the Sun, where the focusing is very rapid, or near 1 AU, where the distance to be travelled at large pitch angles is short, and also those scattered almost in the forward direction. Thus, the relative number of particles arriving during the first minute is higher than $\exp(-1.13/\lambda)$, which represents the theoretical unscattered component.

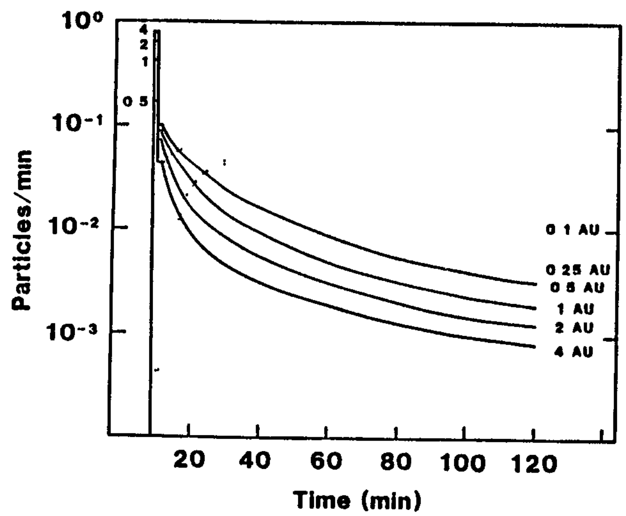

Fig. 1. Intensity-time profiles at 1 AU for various scattering mean free paths.

3.2. The May 7, 1978 Solar Particle Event. On May 7, 1978, an increase in the counting rates of ground level neutron monitors was recorded starting in the time interval 0335-0340 UT. The increase exceeded 50 % at several stations. At Kerguelen, which had its asymptotic directions of approach ideally connected with the apparent source direction, the increase was more than 200 %.

The apparent source direction, which is the direction of the IMF line at Earth, was chosen to be 5 N, 90 E. This was estimated using data from the world-wide network of neutron monitors (Shea et al. 1979). The co-rotational acceptance cone of Kerguelen was calculated by trajectory tracing method. The rigidities ranged from 3 to 10 GV, and also non-vertical directions were included.

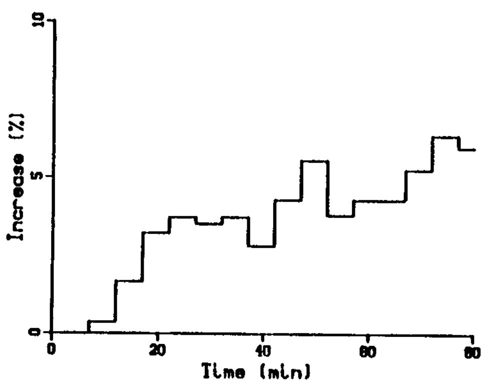

Fig. 2. Increase at "DRI".

Due to the large fluctuations at stations receiving only back-scattered particles, we introduced a fictive station "DRI", where both the counting rate increase and the asymptotic directions are averages of the stations Deep River and Inuvik. The increase at this station is shown in Figure 2. The pitch angle interval it responds to was taken to range from 120° to 160° during the entire event.

An observed intensity profile can be related to several injection profiles depending on the scattering mean free path. By increasing λ, also the injection time has to be increased, since the particle flux decreases faster (see Fig. 1). In the following we illustrate a method, where both injection time and mean free path of pitch angle scattering are deduced simultaneously.

We first parametrize the injection profile as $\exp(-t/\tau)$. At each of the scattering mean free paths, 0.5, 1, 2, and 4 AU, we then calculate the theoretical intensity profiles at Kerguelen for various values of τ. By comparing these profiles with the observed intensity profile we deduce the proper injection profile for each λ. In Figure 3 we show this comparison for λ = 1 AU. The best fit of the (λ,τ) pairs deduced in this way are (0.5 AU, 9 min), (1 AU, 11 min), (2 AU, 12 min), and (4 AU, 13 min).

Using these (λ,τ) pairs we then calculate the anisotropy Kerguelen vs. DRI. In Figure 4 we show these anisotropy curves together with the observed anisotropy. The figure indicates that

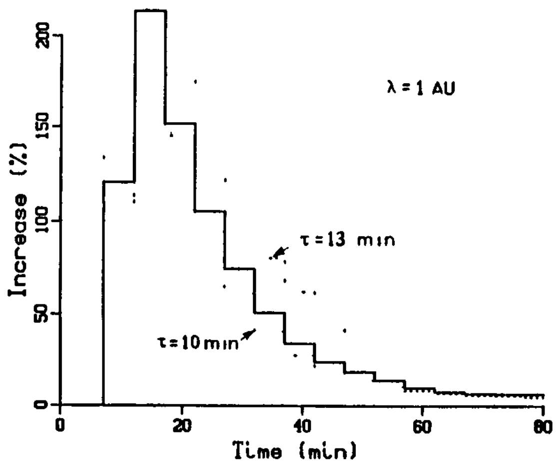

Fig. 3. Comparison between observed increase at Kerguelen (solid line) and increases deduced from Monte Carlo distributions at 1 AU (dotted, normalised at max increase).

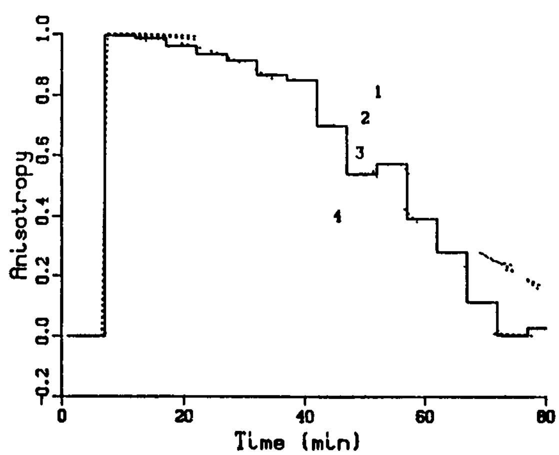

Fig. 4. Anisotropy Kerguelen vs. DRI during the GLE on May 7, 1978. Solid line: observed, dotted lines: theoretical curves: 1. $\lambda = 4$ AU, $\tau = 13$ min; 2. 2 AU, 12 min ; 3. 1 AU, 11 min ; 4. 0.5 AU, 9 min.

$\lambda = 1$ AU and that the decay time of exponential injection is 11 minutes. This scattering mean free path is significantly smaller than the previously published 3 - 5 AU (Debrunner and Lockwood, 1980; Lockwood at al., 1982).

4. CONCLUSIONS

The intensity profiles of the particles after a delta-like injection from the Sun show that the interplanetary propagation is diffusive only at scattering mean free paths below 0.5 AU.

The scattering mean free path during the May, 7, 1978 solar particle event was about 1 AU and represented by exponential form, the injection had a decay time of about 11 minutes.

5. ACKNOWLEDGEMENTS

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REFERENCES

Debrunner H and Lockwood J A, J. Geophys. Res. 85, 6853(1980)
Lockwood J A, Debrunner H, Fluckiger E, Neuenschwander H, and Schubnell M, J.Geophys. Res. 87, 4338(1982)
Shea M A et al., Proc. 18th Int. Cosmic Ray Conf. 5, 226(1979)