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## ENERGY LOSS OF COSMIC RAYS IN THE INTERPLANETARY MEDIUM

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The expansion of the solar wind is likely to cause low-energy cosmic-ray particles to lose a significant fraction of their energy in the interplanetary medium. It is shown that because of this effect, most of the protons observed below ~100 MeV and alpha particles below ~60 MeV/nucleon originate at higher energies, making it impossible to sample directly the interstellar spectra at these energies.

It has been shown<sup>1,2</sup> that cosmic-ray particles lose energy in the interplanetary medium as they are scattered among magnetic irregularities moving outward with the expanding solar wind. In these treatments, the cosmic-ray number density  $U(r, T)$  per unit interval of kinetic energy  $T$  is generally considered to satisfy a spherically symmetric Fokker-Planck equation<sup>1,3</sup>

$$\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 V U) - \frac{1}{3} \left( \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 V) \right) \left( \frac{\partial}{\partial T} (\alpha T U) \right) = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \kappa \frac{\partial U}{\partial r} \right) \quad (1)$$

which allows for the effects of convection, diffusion, and energy loss. Here  $\kappa(r, T)$  is the particle-diffusion coefficient in the radial direction,  $V(r)$  is the solar wind speed, and  $\alpha(T) = (T + 2mc^2)/(T + mc^2)$ , with  $mc^2$  the rest energy of a particle. It is appropriate to assume that the number density varies only in the radial direction. There is, of course, no indication of long-term variations of the cosmic-ray number density with heliocentric longitude, nor is there compelling evidence for significant gradients in the heliocentric polar direction, particularly if there is a thorough mixing of the magnetic field lines due to their stochastic nature.<sup>4</sup>

Equation (1) is difficult to solve analytically with any but the simplest forms of  $\kappa$  and  $U_0$ , the unmodulated interstellar spectrum. There have been, therefore, few attempts to determine the amount of energy cosmic-ray particles are likely to lose in the interplanetary medium using values of  $\kappa$  and  $U_0$  which approximate the actual conditions, although informative calculations of the energy loss have been performed by Parker<sup>1</sup> using a simple analytic solution. Some useful approximations to Eq. (1) have been developed and used to study the energy loss,<sup>5</sup> but in general these approximations are not valid at energies

below, say, 150-200 MeV/nucleon where energy-loss processes should be extremely important. Recently, Fisk<sup>6</sup> has outlined a numerical technique for solving Eq. (1) which is valid at all energies, for general forms of  $\kappa$ ,  $V$ , and  $U_0$ . In the present Letter, we shall use this technique to assess the energy loss in the interplanetary medium by cosmic rays of various interstellar energies, and we shall discuss the influence of this effect on our ability to determine directly the interstellar spectrum at low energies.

In a recent Letter,<sup>7</sup> we compared the observed electron spectrum in 1965 with the interstellar electron spectrum inferred from the nonthermal radio background. We concluded that the modulation of electrons deduced from this technique will not yield a reasonable modulation for protons unless energy loss in the interplanetary medium was taken into account. Using the numerical technique of Fisk,<sup>6</sup> we found that the diffusion coefficient in 1965 could be represented by  $\kappa = 1.5 \times 10^{21} \beta \kappa_1(P) \exp[(r-1)/1.6] \text{ cm}^2 \text{ sec}^{-1}$ , where  $\beta$  is particle speed in units of  $c$ ,  $r$  is in units of A.U., and  $P$  is particle rigidity in units of BV;  $\kappa_1(P) = P$  for  $P \geq 0.35$  BV and  $\kappa_1(P) = (0.35P)^{1/2}$  for  $P \leq 0.35$  BV. We shall continue to use this diffusion coefficient in the present computations, since it appears to provide an adequate description of interplanetary conditions during solar minimum, at least near the orbit of earth. For  $P \geq 0.35$  BV, the magnitude and rigidity dependence of this diffusion coefficient are in excellent agreement with the diffusion coefficient inferred from measurements of the radial gradient of the cosmic-ray intensity in 1965,<sup>8</sup> and up to  $P \sim 6$  BV (where the effects of the modulation are negligible) it is in reasonable agreement with the diffusion coefficient predicted from solar-minimum measurements of the power spectrum of magnetic field fluctuations.<sup>9</sup> A diffusion coefficient

which varies as  $P^{1/2}$  rather than  $P$  at low rigidities is also in agreement with power-spectra predictions.<sup>9</sup> The choice of the radial dependence of the diffusion coefficient, however, is somewhat more subjective. Rather than choosing the exponentially varying diffusion coefficient above, we could choose one which is constant in radial distance out to 2-3 A.U. and thereafter becomes infinitely large, as has been suggested by some studies of the behavior of cosmic rays during solar-flare events.<sup>10</sup> In either case, the principal modulating region lies within a few A.U. of the sun, and predictions of the modulation and energy losses of the particles will be essentially the same. If, however, the modulating region is much larger than we have assumed here, or if there is more modulation beyond the earth than between the earth and the sun, then our estimates of the energy loss will be too small. In any event, our calculations can be considered to be a reasonable lower limit to the actual energy loss, since a modulating region which is smaller

than the one we have assumed above would be inconsistent with the electron modulation deduced from the galactic nonthermal radio emission.<sup>7</sup>

We consider a series of essentially monoenergetic interstellar spectra centered at different energies  $T_0$  and we compute the resultant spectra at Earth using Eq. (1) and the interplanetary parameters given above. The Fokker-Planck equation, when used to determine the differential number density in the frame fixed with respect to the sun (as done in the present Letter), is valid for steep interstellar spectra only if  $\epsilon = (V/c\beta) \partial \ln U / \partial \ln T \ll 1$ .<sup>3,11</sup> We have chosen, therefore, input spectra of the form  $U_0 \propto \exp[-50(\ln T/T_0)^2]$  which satisfy this condition whenever the number of particles present is numerically significant.

The results are shown in Figs. 1 and 2 for protons and alpha particles, respectively. The solid curves represent the various input interstellar spectra and the light dashed curves are the corresponding modulated spectra at Earth. The normalization of the input spectra was chosen so

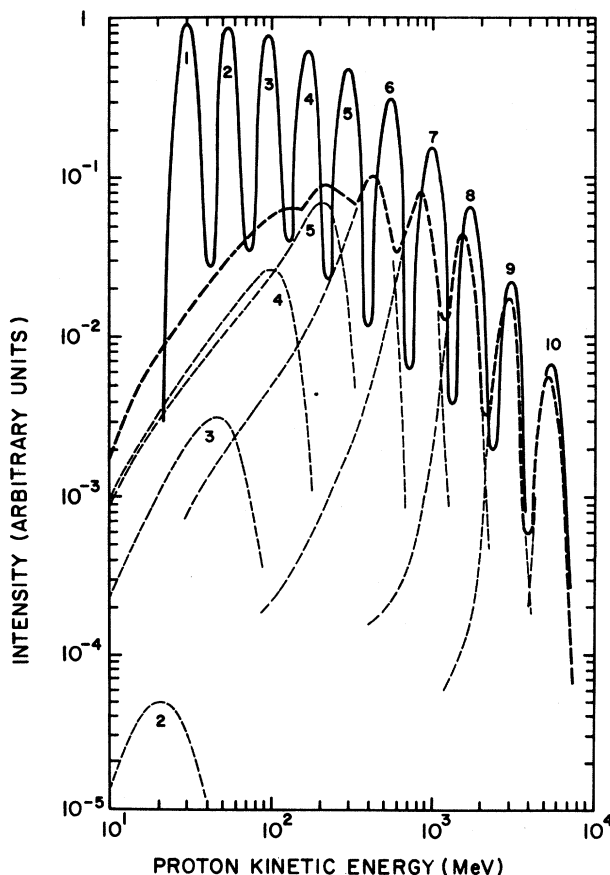


FIG. 1. A series of essentially monoenergetic proton spectra in interstellar space (solid) and their resultant modulated spectra at Earth (dashed).

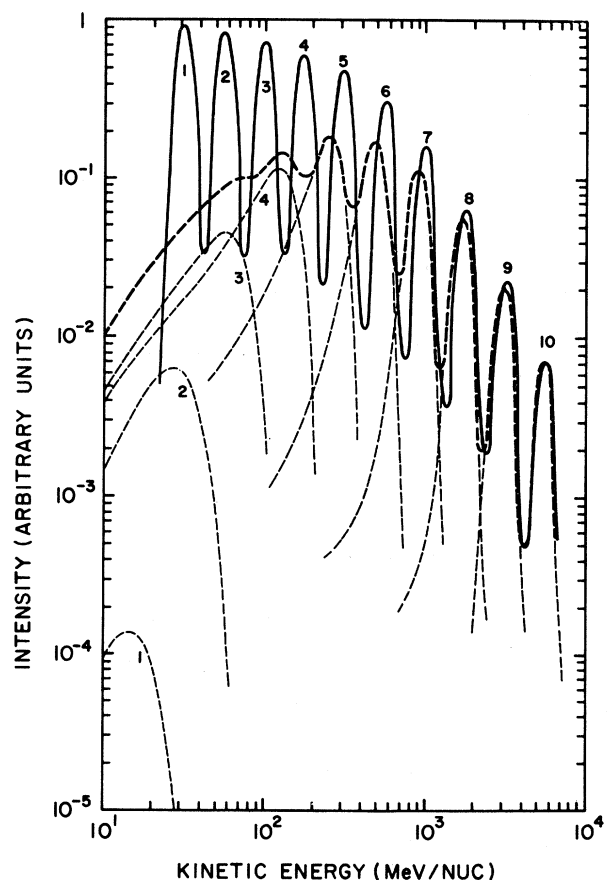


FIG. 2. A series of essentially monoenergetic alpha-particle interstellar space (solid) and their resultant modulated spectra at Earth (dashed).

that their upper envelope is a power law in total energy. The heavy dashed curve represents the sum of all the light dashed curves.

As can be seen, at high energies (curves 9 and 10) the effects of the modulation are negligible. At lower energies, in addition to a net suppression due to diffusion and convection, the effects of energy loss become evident. Down to an energy of several hundred MeV (curve 6) a mean energy loss, as represented by the displacement between the peaks of the modulated and unmodulated spectra, is a useful quantity and can be estimated from Gleeson and Axford's<sup>5</sup> formula for the mean energy loss,  $\varphi$ :

$$\varphi \cong \frac{\alpha T}{3} \int_r^\infty \frac{V dr'}{K} = 210 \text{ MeV} \quad (2)$$

using the diffusion coefficient given above. At lower energies (curves 5 and below) the spread in the modulated spectra is so large that a mean energy loss is no longer a meaningful concept.

The most striking feature which results from the energy loss is that below  $\sim 100$  MeV for protons and  $\sim 60$  MeV/nucleon for alpha particles the modulated spectra become virtually insensitive to the interstellar spectra in the same energy regions. At these energies, the heavy dashed lines are comprised almost entirely of curves 4 and 5 for protons and 3 and 4 for alpha particles, all of which originate at higher energies. The degree to which the low-energy spectra at Earth are insensitive to variations in the interstellar spectrum can be seen from the fact that curve 2 for protons, and curve 1 for alphas, could be increased by more than two orders of magnitude without significantly modifying the observed spectra.

In our previous study,<sup>7</sup> we found that, with the diffusion coefficient given above, a reasonable fit to the proton data in 1965 could be obtained by choosing the interstellar intensity to be a power law in total energy. This result is shown in Fig. 3 together with an alpha-particle spectrum at Earth that was also obtained using an interstellar intensity which is a power law in total energy per nucleon. This choice of the interstellar alpha-particle spectrum gives a good fit to the observed alpha particles, and is consistent with an energy-independent proton-to-alpha ratio in interstellar space. This latter statement, however, can be safely made only for energies greater than  $\sim 100$  MeV/nucleon. Below this energy, as demonstrated above, the energy loss prohibits us from directly sampling at Earth the interstellar parti-

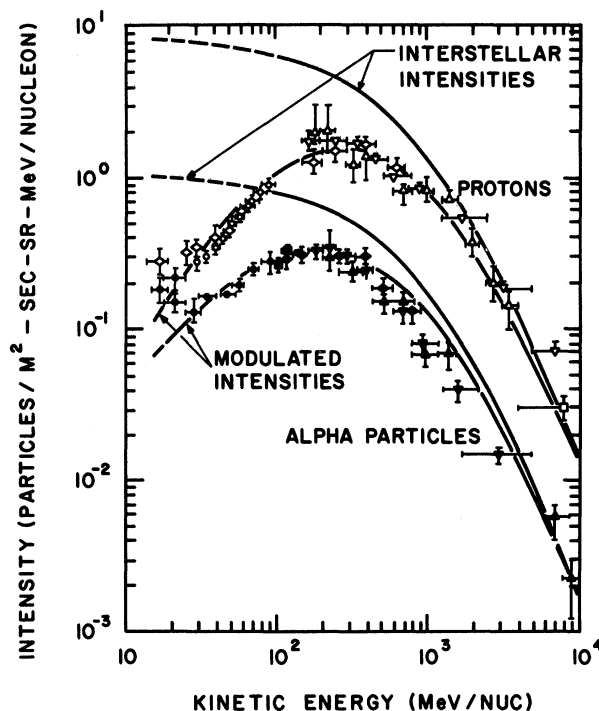


FIG. 3. Proton and alpha-particle spectra. The data were summarized by Gloeckler and Jokipii (Ref. 14), and the modulated intensities were obtained from the interstellar intensities by solving Eq. (1) with interplanetary parameters given in the text.

cles.

In conclusion, because of the energy loss resulting from the expansion of the solar wind, it is not possible to determine the interstellar particle spectra at low energies from direct cosmic-ray measurements at Earth, even if the modulation mechanism were completely understood and the relevant parameters known. For this reason, we cannot determine, for example, whether there is a sufficient number of low-energy cosmic rays to heat the interstellar medium, i.e., significantly more than is predicted by a power law in total energy which was found to be inadequate for this purpose.<sup>12</sup> On the other hand, energy losses make it possible for us to understand the apparent lack of ionization losses of medium and heavy nuclei in interstellar space<sup>13</sup> by noting that most of the particles observed at low energies originate at higher energies where ionization losses are negligible.

It has come to our attention that results similar to the ones presented here have recently been obtained independently by Urch and Gleeson and will appear shortly in another journal.

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# ASYMMETRY IN $\pi^+$ PHOTOPRODUCTION FROM A POLARIZED TARGET AT 5 AND 16 GeV†

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We have measured the asymmetry of the cross section for  $\gamma p \rightarrow \pi^+ n$  from a polarized target at 5 and 16 GeV. The range of four-momentum transfer was  $0.02 \leq -t \leq 1.0 \text{ GeV}^2$ . The  $\pi^+$  mesons were produced in a polarized butanol target and detected with the Stanford Linear Accelerator Center 20-GeV/c spectrometer. A sizable asymmetry was found at both 5 and 16 GeV, a typical value being  $-0.6$  near  $-t = 0.3 \text{ GeV}^2$ . A small amount of data on the asymmetry of other photoproduction processes was also obtained.

Single-pion photoproduction at high energies has received much experimental and theoretical attention in the past several years.<sup>1,2</sup> In the forward direction (small momentum transfer to the pion) the differential cross section has been measured for  $\gamma p \rightarrow \pi^+ n$ ,  $\gamma p \rightarrow \pi^0 p$ , and  $\gamma n \rightarrow \pi^- p$  and  $\gamma$  energies up to 18 GeV. Theoretical models based on Regge poles only, Regge poles with absorptive cuts, vector-meson dominance (VDM), electric Born approximation with and without absorption, and phenomenological fixed poles have been applied to these cross sections. Recently, beams of high-energy linearly polarized photons have allowed measurements of the production asymmetry by photons with states of polarization parallel and perpendicular to the plane of production. A different combination of amplitudes from that measured in the polarized-photon experiments

is measured by photoproducing from a polarized target (see Jackson and Quigg,<sup>3</sup> for example). We report here a measurement of the asymmetry in the produced pions between two states of proton polarization in the reaction

$$\gamma p \rightarrow \pi^+ n.$$

The experiment was performed at the Stanford Linear Accelerator Center, using the 20-GeV/c spectrometer to detect the  $\pi^+$ . The spectrometer system was similar to that used in previous photoproduction experiments of Boyarski et al.<sup>4,5</sup> A butanol polarized-proton target<sup>6</sup> was used in a vertical magnetic field with its proton spins (those of hydrogen nuclei) oriented parallel and antiparallel to the normal of the production plane. The polarizing magnetic field was not altered during the reversal of the target polarization;