PENETRATION OF SOLAR PROTONS AND ALPHAS TO THE GEOMAGNETIC EQUATOR

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Simultaneous spectral observations of low-energy solar particles in interplanetary space and in the magnetosphere on the equator strongly imply that these particles have essentially free access to the outer magnetosphere through a very effective diffusion mechanism which preserves the spectral shapes and the flux magnitudes. These observations further imply that measurements of solar-particle arrival time over the polar caps are not sufficient to distinguish between open or closed magnetosphere models.

A number of investigators making measurements over the polar caps[1] have observed that the low-energy solar protons have cutoff energies that depend on latitude in a manner that departs significantly from the predictions of Störmer's theory[2] and subsequent modifications to more realistic field models.[3] Recent measurements of >40-MeV solar protons at the equator at $L < 5R_E$ were shown also to have cutoffs below the classical Störmer values.[4] Krimigis, Van Allen, and Armstrong,[5] utilizing simultaneous data from an interplanetary satellite and a low-altitude, polar-orbiting satellite, have reported evidence of "essentially immediate access" of 0.5- to 4.2-MeV solar protons to the earth's polar caps. They interpret these results as favoring an "open" magnetosphere model[6] over a more closed model with magnetic merging at several A.U. in the magnetotail.[7]

Reported here are extensive simultaneous spectral measurements of both low-energy solar protons and alpha particles outside the magnetosphere on IMP F (Explorer 34) and inside the magnetosphere on the equatorial satellite ATS-1 during both quiet and disturbed geomagnetic conditions. The observed rapid penetration of both enhanced solar protons and alphas to the equatorial region at $6.6R_E$, the observed preservation of the spectral shapes, and the observed diurnal effects in the protons strongly suggest that there is continuous diffusion of these interplanetary particles across the magnetosphere boundary and deep into the magnetosphere during all times when a source of these particles is present in interplanetary space. The diurnal effect also implies that these solar particles are geomagnetically trapped for several longitudinal drift periods. These observations of solar particle penetration into the outer regions of the magnetosphere cast serious doubt on the validity of interpreting polar-cap measurements of solar protons strictly in terms of open or closed magnetosphere models.

The ATS-1 satellite (launched 6 December 1966) is a geostationary, spin-stabilized satellite (with the spin axis parallel to the local magnetic field) stationed at 150°W, 0°N and at a geocentric distance of $6.6R_E$. The Bell Telephone Laboratories (BTL) experiment flown on ATS-1 consists of a six-element solid-state detector telescope oriented perpendicular to the spin axis of the satellite. By use of the particle dE/dX characteristics and appropriate logic circuitry, the experiment is capable of distinguishing between protons and alphas. The half-angle of the detector telescope collimator is 20°; the flux measured by the BTL experiment is the spin-averaged flux of those particles with pitch angles close to 90°.[8,9] ATS-1 local time is obtained by subtracting 10 h from the universal time.

IMP F, launched 24 May 1967, is a spin-stabilized (with the spin axis perpendicular to the ecliptic plane) polar-orbit satellite with an apogee of approximately $34R_E$. The BTL experiment consists of a four-element solid-state telescope oriented perpendicular to the spin axis. The half-angle of the detector telescope collimator is also 20°; the flux measured by the experiment is the spin-averaged flux of particles in the ecliptic plane. Protons and alphas up to an energy of approximately 4 MeV/nucleon are distinguished by the energy deposited in the first two detectors of the telescope and subsequently measured in a five-channel analyzer. Particle species above this energy are distinguished by the use of an on-board pulse multiplier.[10]

$\frac{1}{2}$-h averages of the interplanetary (IMP, 1.2-2.5 MeV) and magnetosphere (ATS, 1.9-2.8 MeV) proton data for days 164-181, 1967, are plotted in Fig. 1. The data for days 220-225, 1967, are plotted in Fig. 2. The periods when the IMP satellite was within $10R_E$ of the earth are indicated. The 6-h counting rates for time intervals centered about ATS local times of noon, 1800, mid-

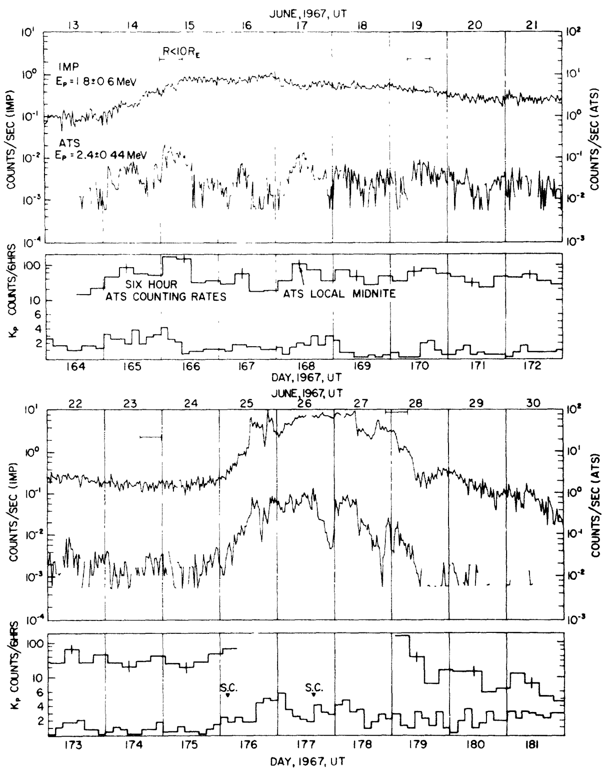

FIG. 1. Simultaneous interplanetary and equatorial magnetosphere solar-proton data—June, 1967.

night, and 0600 are plotted immediately below the $\frac{1}{2}$-h averaged data in Fig. 1. Plotted at the bottom of both figures are the 3-h-averaged K_p data indicating the geomagnetic activity in the time intervals discussed.

The data plotted in Fig. 1 correspond to the 18-d period between 13 June and 30 June which followed the three solar-flare particle events on 23 and 25 May and 6 June 1967.[11,12] The interplanetary flux of 1.2- to 2.5-MeV protons from day 164 to day 176 is larger than is normally observed. From days 167 to 176 the interplanetary proton fluxes decayed by approximately a factor of 5. This same overall decay was also observed in the proton fluxes inside the magnetosphere.

The 6-h ATS proton data in Fig. 1 show a diurnal variation during most of the rather quiet geomagnetic period up to day 176. During this entire period a diurnal effect similar to that reported previously,[11] and opposite to these proton variations, was observed in the electron data. The maximum in the proton diurnal fluxes generally occurred in the 6-h interval centered around local midnight and the minimum generally occurred in the 6-h interval centered around local noon. This is the same type of proton diurnal behavior observed during portions of the 25 January solar event.[13,14] During the two geomagnetically very quiet days 174 and 175, when the interplanetary fluxes were low, the diurnal effect was reversed with more protons measured at local noon than at local midnight.

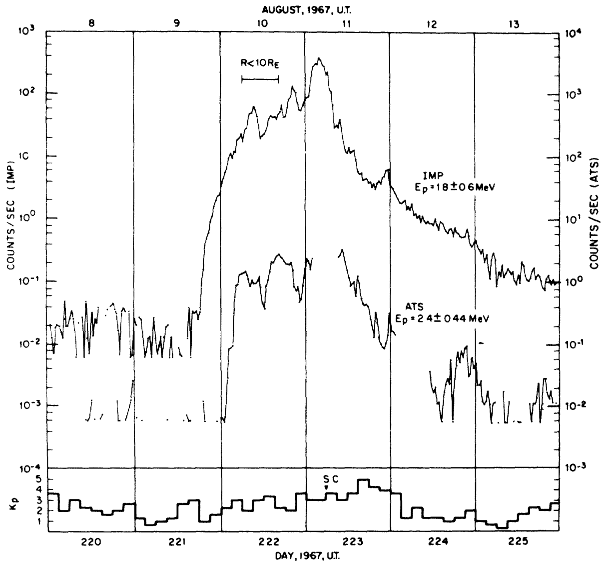

FIG. 2. Simultaneous interplanetary and equatorial magnetosphere solar-proton data—August, 1967.

Figures 3(a) and 3(b) show 6-h-averaged proton spectra from IMP and ATS centered about 1200 (noon) and 2400 (midnight) day 167, ATS local time. The higher energy ATS proton fluxes at both times are approximately equal to the interplanetary fluxes; both spectra fall off at the lower energies, with the largest falloff occurring at local noon. The effective L value at the ATS altitude during these two local time periods is different because of the solar-wind distortion of the magnetosphere.[15] Since magnetic field data from ATS were not yet available, the diurnal variations in the electron fluxes observed by the BTL experiment[9] were used to estimate indirectly the amount of magnetosphere distortion. The electron diurnal variations during days 167 and 168 were compared with available simultaneous electron and magnetic-field data obtained during the first two weeks of 1967. These comparisons were used with Roederer's computations of a model magnetosphere[15,16] and indicated that on day 167 the magnetosphere boundary was near $10.5R_E$ and that the ATS satellite was measuring protons near $L = 6.0$ at local noon and $L = 6.6$ at local 2400(midnight).

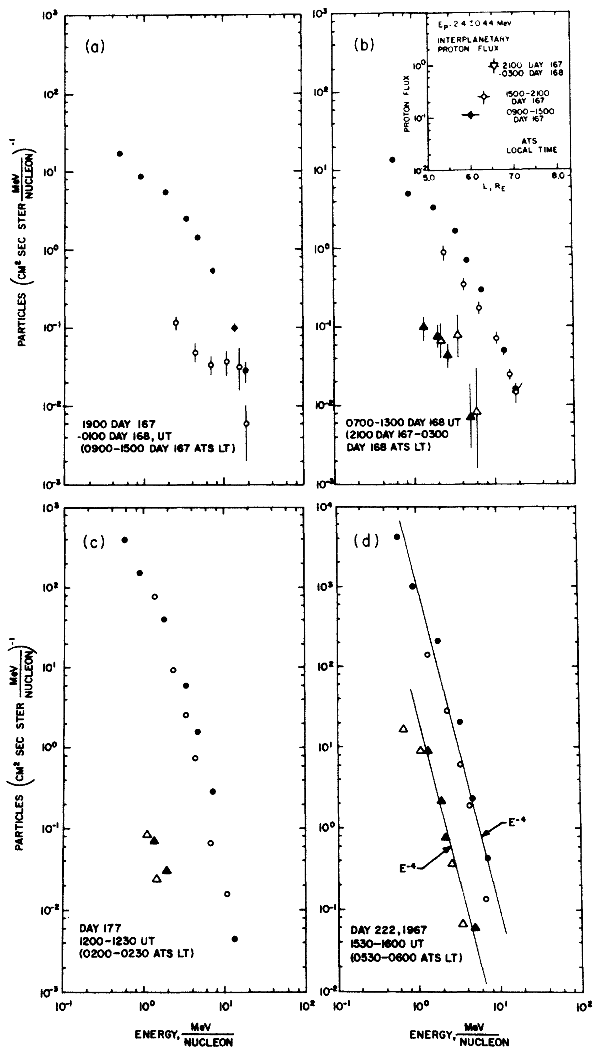

FIG. 3. Interplanetary (solid points) and equatorial magnetosphere (open points) particle fluxes. Circles correspond to protons; triangles correspond to alpha particles. The data points in the inset in (b) are protons.

The inset in Fig. 3(b) shows the 1.9- to 2.8-MeV ATS proton data plotted as a function of L during day 167 ATS local time in order to indicate the relationship of the ATS proton fluxes to the same energy proton fluxes measured on IMP. This plot suggests that the magnetosphere fluxes and spectra at approximately $L = 7$ would be equal to the interplanetary fluxes and that the proton intensities decrease strongly below $L \sim 7$.

The increase in the flux of interplanetary protons observed near the beginning of day 176 (Fig. 1) apparently resulted from the reappearance after one solar rotation of the region associated with the 28 May solar-flare event.[12] At the time of the flux increase IMP F was outbound at a distance of $\sim 30R_E$, an angle to the ecliptic of ~23°, and a sun-earth-probe angle of ~80° east, while ATS-1 was at approximately 1400 local time.

The proton increase in interplanetary space was accompanied within $\frac{1}{2}$ h by an increase in the proton fluxes measured at ATS. (The timing uncertainties are not instrumental but statistical, due to the gradual interplanetary increase.) The drop in fluxes on day 179 also occurred simultaneously within $\frac{1}{2}$-1 h both outside and inside the magnetosphere. Although there is not always a one-to-one correspondence during the entire event (the larger dip in the ATS flux during the latter part of day 177 occurred at the time of the second sudden commencement storm; a similar dip was observed during the 28 May event[12]), the overall correspondence between the interplanetary flux increases and decreases and the simultaneous equatorial magnetosphere response is indeed striking.

The solar proton event shown in Fig. 2 occurred during an August geomagnetically quiet day while IMP F was inbound at a distance of $20R_E$ with an ecliptic angle of 23° and an earth-sun-probe angle of ~35° east. ATS-1 was approximately at local 0800 at the time of the interplanetary proton increases and observed the first flux increase some six hours later, at approximately 1400. Hence, during the geomagnetically quiet period after the solar protons were initially observed in interplanetary space there was an approximately 6-h time delay before the protons were seen inside the magnetosphere. However, within 3-4 h after the protons were first observed on ATS-1 (while the geomagnetic disturbance was increasing), the interplanetary and the magnetosphere proton increases and decreases again had a striking resemblance.

Proton and alpha spectra during a period of enhanced fluxes of both day 177 and day 222, 1967, are shown in Figs. 3(c) and 3(d). During both periods the proton and alpha fluxes inside and outside the magnetosphere were approximately equal. Both the proton and alpha spectral shapes were very similar; there was no evidence of a low-energy falloff.

The electron diurnal data observed by the BTL experiment during days 164-175 imply that the ATS experiment was measuring particles on closed longitudinal drift shells. Hence the "inverse" diurnal variation in the quiet-time proton data implies that the protons were stably trapped for a time period of the order of a few longitudinal drift periods ($\tau_D \sim 8$ min for 1-MeV protons at synchronous altitude) and that their source was beyond $L \sim 7$. The facts that no magnetosphere protons were observed when the interplanetary source was absent and that a proton and alpha enhancement in the magnetosphere did not persist after the source was absent also imply that the protons and alphas are trapped for only a few drift periods and certainly not for more than a few hours. The fact of proton trapping rules out the possibility that these protons entered the magnetosphere by field-line connection either to the magnetotail[7] or to interplanetary space over the poles.[6] The rapid access of the enhanced interplanetary particles to the equatorial region further rules out access via the geomagnetic tail where the merging in the tail is believed to take place at several A.U.

The observed "inverse" diurnal effect and the observed rapidity with which the equatorial regions of the magnetosphere respond to an enhanced interplanetary flux of protons and alphas strongly suggest that a diffusion mechanism is continually operative in the outer magnetosphere and not just at the times of magnetic sudden commencements or sudden impulses.[17] The interplanetary-magnetosphere response-time difference observed between quiet and disturbed geomagnetic times is indicative that the diffusion mechanism is probably stronger during a more disturbed condition. In addition, during a disturbed geomagnetic condition, the magnetosphere boundary is closer than during a more quiet period. Furthermore, the similarity of the particle spectra observed inside and outside the magnetosphere, particularly during the times of enhanced fluxes, implies that the diffusion mechanism preserves the spectral shapes of the interplanetary protons and alphas. The similarity of the magnitude of the magnetosphere particle fluxes to the enhanced interplanetary source fluxes over a wide energy range suggests that the diffusion mechanism violates the first adiabatic invariant.

During the geomagnetically quiet times, the value of L near ATS local noon was ~6, corresponding to a geomagnetic latitude of ~63° at the surface of the earth. During geomagnetically active times much higher flux values of protons were observed at the ATS altitude and some protons were thus presumably seen at lower L values, corresponding to lower latitudes. It is possible that the latitude lowering for low-energy solar particles observed on polar-orbiting satellites during geomagnetically disturbed conditions is simply a reflection of the fact that solar particles can diffuse faster and with more intensity to lower equatorial altitudes during these times. These protons are then rapidly pitch-angle scattered so that they are seen at the lower altitudes over the polar caps and in the auroral zones. The short trapping times attributed here to the equatorially mirroring particles could then be due to a combination of particle loss due to pitch-angle scattering and diffusion back out of the magnetosphere.

In conclusion, the simultaneous solar proton and alpha-particle observations discussed above strongly imply that there is a very effective continuous diffusion of the interplanetary-source particles into the outer equatorial magnetosphere. The strength of the diffusion is strongly dependent upon the intensity of the geomagnetic activity. The observations also imply that these particles are geomagnetically trapped for only a few longitudinal drift periods. Finally, the existence of a diffusion mechanism for producing rapid solar-particle penetration into the outer regions of the magnetosphere and the short trapping time of these particles strongly imply that measurements of the solar-particle arrival time in interplanetary space and over the polar caps are not sufficient to distinguish between open or closed models of the magnetosphere.

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PHOTOPRODUCTION OF π^0 MESONS FROM HYDROGEN AT 180°†

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We measured the π^0 photoproduction differential cross section at 180° for a range of incident photon energies between 650 and 1750 MeV. The cross sections are dominated by the $D_{13}(1525)$, $D_{15}(1688)$, and $F_{37}(1920)$ resonances.

We have measured the differential cross section for the reaction $\gamma+p \rightarrow \pi^0+p$ at a pion production angle of 180° with respect to the incident photon beam. The recoil protons were momentum analyzed by a magnetic spectrometer (see Fig. 1) which has a momentum resolution of 1.5% determined by two scintillation counters at the focus of the first quadrupole-doublet magnets. The solid angle of the spectrometer was determined by a 1-in.-diam lead collimator placed in the entrance of the first quadrupole magnet. The acceptance of the spectrometer was calculated by a computer program which took into account the physical size, angular distribution, and the energy spectrum of the bremsstrahlung beam, and the ionization loss and the multiple-scattering divergence of protons which went through the 7.5-in. liquid-hydrogen target.

The experimental data were taken with the momentum acceptance of the spectrometer set higher than the energy of the Cornell 2-GeV electron synchrotron in order to accept those protons which could only be produced by photons whose energy was 6% or more below the synchrotron energy. Particles which traveled through the spectrometer were found to have a unique time of flight between the momentum defining counters and the last counter. This information enabled us to separate the protons from 0.5% of chance events. No attempt has been made to delete the protons from elastic photon-proton scattering process which, we assume, is at most a few percent of the π^0 cross section as at other energy and angular regions.[1] A series of tests was made with fixed spectrometer momentum setting and different bremsstrahlung beam energies. From these tests we found that the two-pion contribution is less than 2%. We also made phase-space fits to Deutsches Elektronen-Synchrotron bubble-chamber data[2] on di-pion production and obtained approximately the same result.

Figure 2 shows the results of this experiment.

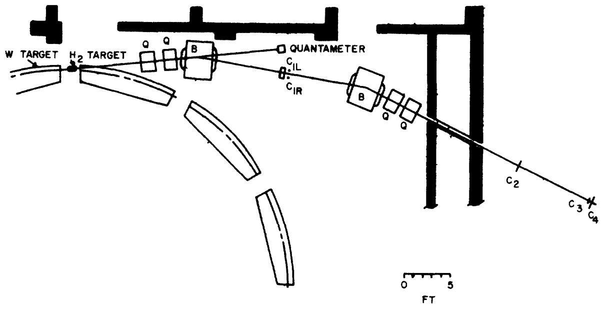

FIG. 1. Experimental layout. Quadrupole magnets, Q; bending magnets, B; scintillation counters, $C1L$, $C1R$, $C2$, $C3$, and $C4$.

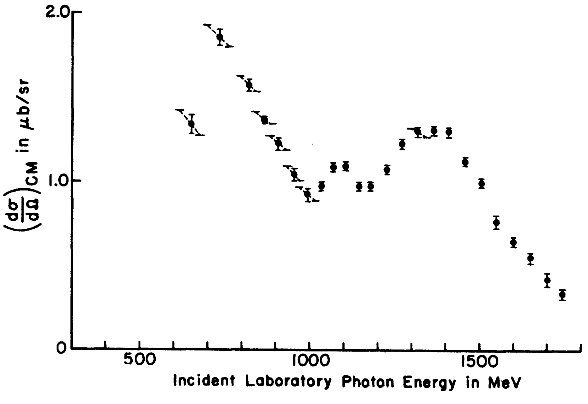

FIG. 2. π^0 photoproduction differential cross section.