# INNER-BELT PROTONS AND RADIAL DIFFUSION*

J. F. Crifo
Sérvice d'Aeronomie, Centre National de la Recherche Scientifique, Verrieres-Le-Buisson, Essonne, France

and

F. S. Mozer
Physics Department and Space Sciences Laboratory, University of California, Berkeley, California
(Received 23 June 1967)

Soon after the discovery of the radiation belts[1] a theory was advanced to explain them as energetic protons trapped in the earth's magnetic field following the beta decay of neutrons produced by cosmic-ray interactions with the upper atmosphere.[2] While this theory accounted for the more energetic protons observed,[3] it soon became clear that such a source was too weak to explain the 1- to 20-MeV protons found at geocentric altitudes below 2 Earth radii[4] or to explain the large electron fluxes also present at such locations.[5] Thus, a much stronger source was required to explain the experimental data.

Analyses of the dynamic motions of charged particles in the magnetosphere under the influence of certain classes of magnetic or electric field variations have indicated that such particles diffuse radially across magnetic field lines and are energized during diffusion if the net motion of the particles is inward.[6-8] This fact has been utilized to generate a class of radial diffusion theories in which a low-energy, strong source at geocentric altitudes of about 10 Earth radii serves to supply the radiation belt with its protons and electrons. The most quantitative estimates of proton intensity as functions of altitude and energy that have been obtained from this radial diffusion theory have utilized the magnetic disturbances associated with sudden commencements and sudden impulses as the driving mechanism responsible for the diffusion.[10] The reasonable agreement between this theory and experiment has led to the generally accepted conclusion that the low-energy protons observed at geocentric altitudes of a few Earth radii have diffused inward from about 10 Earth radii and have been energized by a factor of several hundred in the process. The major uncertainties of this theory are the mechanism determining the lifetime of the diffusing particles and the detailed intensity and time dependences of the field variations driving the diffusing process.

This theory has been compared with measurements of protons having energies of hundreds of keV only at geocentric altitudes above about 2 Earth radii because no experimental data have been collected previously on such particles at lower altitudes. Since the diffusion coefficient of the theory that is based on the magnetic disturbances associated with sudden commencements and sudden impulses varies as the tenth power of altitude and the lifetime decreases rapidly with decreasing altitude due to atmospheric energy loss and charge-exchange reactions, the intensity of inward-diffusing low-energy protons should decrease rapidly below geocentric altitudes of about 2 Earth radii.[10] Thus, measurements of the low-energy, low-altitude, proton flux provide a critical test of the adequacy of diffusion theory to explain uniquely the inner radiation belt.

It is the purpose of the present paper to describe a measurement of protons with energies between 0.5 and 150 MeV made near $L=1.5$, $B=0.18$, on a French sounding rocket launched from Algeria on 30 September 1965 to an altitude of 1750 km. (For a discussion of the $B, L$ coordinate system, see McIlwain.[11]) Analyses of the data indicate the following:

(1) Theories of radial diffusion driven by only the magnetic disturbances associated with sudden commencements and sudden impulses fail by many orders of magnitude to explain the observed flux of protons with energies near 500 keV at $L=1.5, B=0.18$.

(2) Radial diffusion due to other possible classes of magnetic and electric field variations qualitatively explains the proton observations. There is insufficient experimental knowledge of the amplitude of these field variations to attempt quantitative comparisons of proton and field data.

The instrument used to perform the experiment consisted of two solid-state detectors operated as a $dE/dx$-$E$ counter system. The first detector was a disk-shaped, windowless, diffused, *pn* junction with a 43-mg/cm$^2$ depletion layer. It was followed by a conical-shaped lithium-drifted detector that was 2.4 g/cm$^2$ thick. A 15° half-angle mechanical aperture defined the detector geometric factor which was 0.066 cm$^2$ sr for particles producing pulses in both detectors and 0.12 cm$^2$ sr for particles stopping in the first detector. Other than over its entrance aperture, the instrument was surrounded by an 18-g/cm$^2$-thick lead shield on which was placed a 2.7-g/cm$^2$-thick Lucite layer to protect against bremsstrahlung production. Protons with energies between 450 keV and 4.7 MeV were counted as events occurring only in the thin detector (after subtraction of the less than 1% isotropic background arising from particles penetrating the shielding). Protons from 5 to 50 MeV were identified from pulses occurring in coincidence in the two detectors. Electrons were nominally unable to deposit sufficient energy in the thin detector to be counted and they were thus recorded as events occurring only in the thick detector. The above identifications were performed by combining the outputs of the eight-channel pulse-height analyzers associated with each detector through appropriate coincidence and/or anticoincidence circuits to obtain the counting rates of events having given energy losses in the two detectors. In this way, alpha particles have also been separated from protons and electrons and their flux has been estimated. The detector system was calibrated before the flight with monoenergetic protons between 100 and 600 keV, deuterons between 2 and 12 MeV, and electrons from 80 keV to 2.5 MeV.

In Fig. 1, two energy spectra of protons with pitch angles of 90° are presented. Data from other experiments at similar locations in space[12,13] are included in this figure to facilitate comparisons. The present data have also been compared with those obtained on Relay 1 by Fillius and McIlwain,[14] and agreement to within a factor of 2 has been found over the energy range of 1.1 to 35 MeV. It is concluded that the present experiment agrees with earlier results in the energy interval above 1 MeV where earlier data exist.

The most surprising feature of the proton data of Fig. 1 is, thus, the large increase in the directional, differential proton intensity at energies below about 1 MeV. That this increase is not due to electron contamination

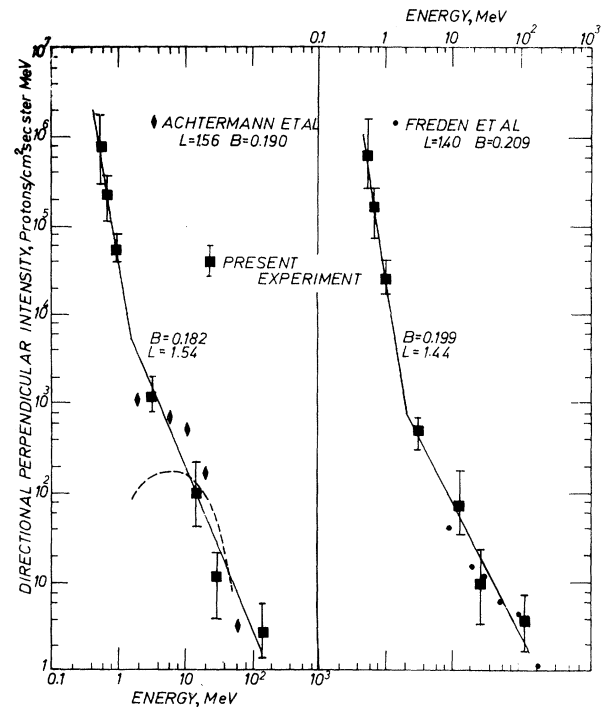


FIG. 1. Proton spectra measured at two times during the rocket flight. Included for comparison are experimental data of Achtermann, Freden, and Hovestadt (Ref. 12) and Freden, Blake, and Paulikas (Ref. 13) as well as the theoretical calculation of Nakada and Mead (Ref. 10), illustrated as the dashed curve. This theoretical curve has been normalized to the experimental data.

of the proton data channels has been shown by examination of the experimental data and by direct computation. It is recalled that protons with energies below 4.7 MeV were identified as anticoincidence events occurring in the thin detector only. Electrons of any energy were nominally not counted by the thin detector because their average energy loss was about 20% of that required to trigger the thin-detector pulse-height analyzer's lowest energy channel. Since multiple-scattering processes can cause some fraction of the incident electrons to lose as much as five times their average energy loss in the thin detector, it is necessary to investigate the possibility of electron contamination in more detail. In Fig. 2, the nominal proton and electron counting rates at pitch angles of 90° are plotted as functions of the magnetic field intensity for the data collected over the region of $L = 1.4$ to $L = 1.54$. The nominal proton counting rate is the anticoincidence counting rate in the thin detector while that for the

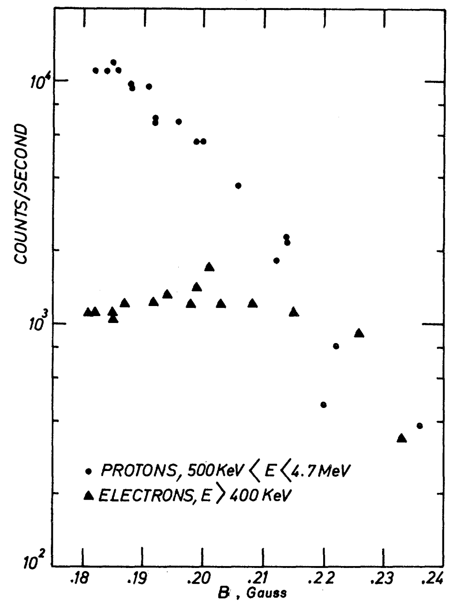


FIG. 2. Comparison of nominal proton and electron counting rates measured over the interval $L = 1.40$ to $L = 1.54$. The nominal proton and electron counting rates are defined as the anticoincidence counting rates in the thin and thick detectors, respectively.

electrons is the anticoincidence counting rate in the thick detector. Since the ratio of the two curves of Fig. 2 varies with $B$, it follows that the magnitude of the electron contamination of the lower energy proton data of Fig. 1 can be, at most, a few percent. This conclusion has been verified by Monte Carlo calculations of the expected multiple-scattering energy loss using results supplied by Berger.[15]

The possibility that the observed counting rate arose through pile-up of a large flux of electrons with energies below 450 keV has been ruled out on the following two grounds: (1) The observed spectral shape is constant over a two-orders-of-magnitude variation of counting rate, which is not possible if pile-up is important since the higher energy counting rate would vary as a higher power of the incident flux than would the lowest energy counting rate. (2) The pile-up counting rate computed from the low-energy electron flux measured by Mihalov and White[16] or estimated from extrapolation of the electron flux of Fig. 2 to lower energies is at least $10^4$ times smaller than the observed rate.

A comparison of the experimental data with theoretical calculations based on diffusion theory will next be presented. Since atmospheric interactions increase rapidly with decreasing energy, it might be expected that the proton energy spectrum should peak at some energy and that the proton intensity at lower energies would be less. In Fig. 1, the theoretical energy spectrum obtained at $L = 2$ by Nakada and Mead[10] using sudden-commencement and sudden-impulse magnetic fluctuations as the diffusion source is plotted as the dashed curve. The four to five orders of magnitude disagreement between theoretical and experimental spectral shapes can be decreased by the assumption of a different source spectrum near $L = 10$ than that assumed by these authors. Addition of the low-energy source protons required to explain the present data would, however, result in an expected low-energy proton flux near $L = 2.5$ that is about $10^4$ times larger than that measured by Davis and Williamson.[17] And thus, the shape of the proton spectrum near $L = 1.5$ is in disagreement with diffusion theories based on magnetic field variations associated with sudden commencements and sudden impulses.

A more serious criticism of any attempt to add a sufficient low-energy flux to the high-altitude radial diffusion source in the theory of Nakada and Mead is that such protons, while diffusing inward, would represent a particle energy density that is orders of magnitude larger than the magnetic field energy density, $B^2/8\pi$, over a major part of the outer radiation belt. The ratio of particle-to-field energy densities computed from the results of Nakada and Mead (extrapolated to $L = 1.5$) under the assumption that the protons observed in the present experiment diffused inward from high altitudes is near 1 at $L = 2$, near 100 at $L = 3$, and near 10 000 at $L = 7$. And thus, in the context of diffusion theories using only magnetic variations associated with sudden commencements and sudden impulses, it is concluded that the observed protons at $L = 1.5$ could not have diffused inward from high altitudes because the magnetic field could not have contained the large particle energy density that would have been present at larger $L$. That the present data disagree with the theory of Nakada and Mead by orders of magnitude near $L = 1.5$ is not surprising since this theory and earlier experiments disagree by at least an order of magnitude near $L = 2$ and the disagreement increases rapidly with decreasing $L$.[10]

If the protons diffused radially at small $L$ at rates substantially greater than assumed in the theory of Nakada and Mead, a smaller source strength at large $L$ would suffice to produce the required low-altitude intensity. By adjustment of the diffusion coefficient, it would thus be possible to decrease the source requirement until the ratio of particle to field energy densities does not exceed 1 at large $L$ while the theoretical flux of 500-keV protons near $L=1.5$ is as large as measured. To maintain agreement with experimental data at $L=2.5$ and beyond, the diffusion beyond $L \sim 3$ could not be much faster than that deduced by Nakada and Mead. The above requirements on the diffusion rates can be satisfied by diffusion coefficients that vary less rapidly with altitude than the tenth-power dependence of the theory based on magnetic field changes associated with sudden commencements and sudden impulses as the diffusing mechanism. Indeed, depending on the power spectrum of the disturbance causing the radial displacement, diffusion coefficients varying with powers of altitude between 6 and 10 may be obtained.[18] Qualitative estimates of particle fluxes obtained with a diffusion coefficient proportional to $r^6$ indicate that both the earlier[17] and the present data may be explained in this fashion. In addition, it is possible that the diffusion coefficient may actually increase with decreasing altitude at sufficiently low altitudes because of terms involving the symmetric spatial component of the magnetic or electric disturbance and the higher order multipoles of the earth's magnetic field.[19]

In addition to magnetic and electric disturbances of types other than those arising from sudden commencements and sudden impulses being important in the diffusion of the observed protons, it is possible that the correct explanation of these protons requires their association with low-energy protons injected impulsively to geocentric altitudes as low as 3 Earth radii during magnetic storms. Recent measurements have shown that low-energy protons reach such altitudes during the main phase of magnetic storms and that these protons may be the agent responsible for the main-phase magnetic field depression.[20] Since the data of the present experiment were obtained about one day after the start of a magnetic storm, it is possible that the observed 500-keV protons are ring-current particles that diffused inward. If this is the case, fluxes as large as those observed are not typical of the inner belt during quiet periods.

---

*Work supported by the French National Center for Space Studies and National Science Foundation Grant No. GA-918.

[1]J. A. Van Allen, G. H. Ludwig, E. C. Ray, and C. E. McIlwain, Jet Propulsion 28, 588 (1958).

[2]S F. Singer, Phys. Rev. Letters 1, 181 (1958).

[3]S. C. Freden and R. S. White, Phys. Rev. Letters 3, 9 (1959).

[4]S. C. Freden, in Radiation Trapped in the Earth's Magnetic Field (D. Reidel Publishing Company, Dordrecht, Holland, 1966).

[5]P. J. Kellogg, J. Geophys. Res. 65, 2705 (1960).

[6]E. N. Parker, J. Geophys. Res. 65, 3117 (1960).

[7]L. Davis, Jr., and D. C. Chang, J. Geophys. Res. 67, 2169 (1962).

[8]B. A. Tverskoy, Geomagnetism i Aeronomiya 3, 351 (1964).

[9]J. W. Dungey, W. N. Hess, and M. P. Nakada, in Space Research, Proceedings of the Fifth International Space Symposium, Florence, Italy, 1964, edited by D. G. King-Hele, P. Muller, and G. Righini (North-Holland Publishing Company, Amsterdam, 1965), pp. 399-403; J. Geophys. Res. 70, 3529 (1965).

[10]M. P. Nakada and G. D. Mead, J. Geophys. Res. 70, 4777 (1965).

[11]C. E. McIlwain, J. Geophys. Res. 66, 3681 (1961).

[12]E. Achtermann, S. C. Freden, and D. Hovestadt, "Measurement of protons in the inner radiation belt by means of a sounding rocket" (to be published).

[13]S. C. Freden, B. Blake, and G. Paulikas, J. Geophys. Res. 70, 3111 (1965).

[14]R. W. Fillius and C. E. McIlwain, "A survey of inner zone protons," University of California, San Diego, Report, 1965 (unpublished).

[15]M. J. Berger, private communication.

[16]J. D. Mihalov and R. S. White, J. Geophys. Res. 71, 2217 (1966).

[17]L. R. Davis and J. M. Williamson, in Radiation Trapped in the Earth's Magnetic Field (D. Reidel Publishing Company, Dordrecht, Holland, 1966).

[18]C.-G. Fälthammar, J. Geophys. Res. 71, 1487 (1966).

[19]C.-G. Fälthammar, private communication.

[20]L. Frank, University of Iowa Research Report No. 67-9, 1967 (unpublished).