By comparison, the accepted value of the Compton wavelength of the free electron is roughly

$$h/mc = 2.43\times 10^{-12}\text{ m}.$$

This type of experiment is somewhat similar to the Michelson-Sagnac experiments with light. The physical source of the phase shift differs, but the formal expressions are identical.[6] There is also, of course, a direct connection between these quantum effects and the classical London moment.[7,8] In a superconductor the action function [the argument of the cosine in (1)] must be zero, thus connecting a rotation (Ω) to a field (B) as

$$\vec{B} = -(2m/e)\vec{\Omega}.$$

Here B is the internal field generated by the rotation (Ω) of an infinitely long superconducting cylinder.

We believe these experiments serve as an additional demonstration of macroscopic quantum effects in superconductors and provide a direct measurement of the quantum of circulation, h/m, for superconducting electrons.

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RADIAL DEPENDENCE OF ENERGETIC ELECTRON FLUXES IN THE TAIL OF THE EARTH'S MAGNETIC FIELD*

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The NASA scientific satellite IMP-1 has made possible the detection of energetic electron fluxes of terrestrial origin out to a geocentric distance of 31.5 earth radii (about 200 000 kilometers). The major axis of the satellite's orbit changed orientation with respect to the sun-earth line by about one degree per day. The distribution of electron flux >45-keV kinetic energy thus could be determined also as a function of sun-earth-satellite angle. This angle should be extremely important for discussing terrestrial energetic particle fluxes, since the solar wind contains the distant geomagnetic field and aligns it in the sun-earth direction. This tail-like structure of the distant field was indicated by magnetometer measurements on Explorers X[1] and XIV[2] and in greater detail by IMP-1.[3] Beyond 10 earth radii geocentric distance and near the midnight meridian the field lines deviate markedly from dipole-like character. The field lines become aligned with the sun-earth line and show no sign of closing even at $31.5R_e$.[3] Trapping of charged particles, if it takes place at all, occurs on a scale entirely different from the Van Allen region. The purpose here is to describe the general character of energetic electron fluxes in the tail of the geomagnetic field and to show the radial dependence of their occurrence. The results come from thin-window Geiger-Mueller tubes arranged to discriminate against proton and bremsstrahlung counts. Details of this apparatus and some results obtained with it have already been published.[4]

Some observations of energetic particle fluxes near the midnight meridian beyond the Van Allen trapping region have already been reported.[5,4] It was shown that substantial fluxes of energetic electrons frequently occur in these regions at much larger radial distance than they do on the sunlit side of the earth. An example of the Geiger-tube rate near the midnight me-

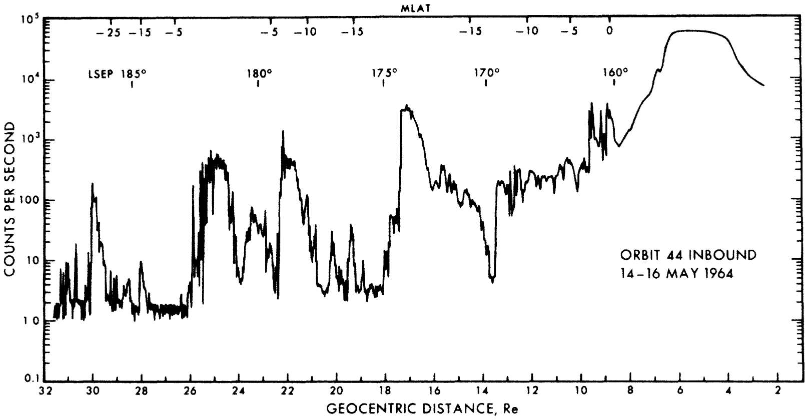

FIG. 1. An inbound pass through the tail of the magnetosphere shows the island-like appearance of the energetic electron flux. Electron fluxes in this region are strongly dependent on geomagnetic activity, so other orbits may show fewer islands. To obtain the electron flux >45 keV in $\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$, multiply counts per second by 7000.

ridian is shown in Fig. 1. The stably trapped radiation zone can be seen from about $1.5R_e$ out to approximately $8R_e$. Electron fluxes in the form of patches or islands having peak fluxes up to a few times $10^7\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$ are seen beyond the trapping boundary all the way out to apogee. The new result to be discussed here is that the electron fluxes in the tail observed at the satellite show two characteristic time constants, one on the order of one minute and the other many minutes to a few hours, and for nearly all the electron islands occurring in the tail the short time constant occurs at early times followed at later times by the longer time constant. The phrase "time constant" at this stage of the discussion simply refers to the rise and fall of the Geiger-Mueller tube counting rate. Figure 2 gives examples of electron islands showing this feature. Some islands have a simple form as in Figs. 2(a) and 2(b); others show a more complex appearance as in Figs. 2(c) and 2(d). In all these examples the occurrence of rapid changes at earlier times followed by the slower decay is marked. The ionization chamber carried on IMP-1 responds to the more intense electron fluxes. It also exhibits the fast-rise, slow-decay response to these fluxes so that the counting rate profiles in Figs. 1 and 2 represent true behavior of the energetic electron fluxes.

A total of 126 energetic electron islands having peak flux greater than $10^5\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$ were

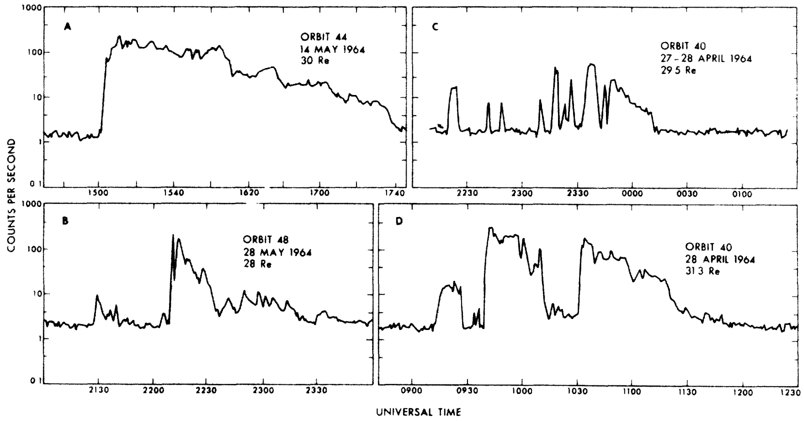

FIG. 2. Examples of electron flux in the geomagnetic tail. The rapid rise of the electron flux followed at later time by a slow decay is characteristic. Note that the rapid switching of the electron flux may occur several times during one event. In these examples (a) is from an inbound pass, (b) and (c) from outbound passes, and (d) occurs near apogee.

present on 17 orbits in the tail region. This flux is about 10 times the minimum detection sensitivity for electron fluxes. In 92 of these cases, the fast-slow pattern was discernible. 31 islands out of the total of 102 were of the simple type exemplified by Figs. 2(a) and 2(b) and had rise times less than 5 minutes and decay times greater than 15 minutes. These were divided about equally between inbound and outbound portions of the orbits. Examples of the mirror image (rise time greater than 15 minutes, decay time less than 5 minutes) were also sought. Only two such examples could be found. The observation that the particle flux nearly always builds up much more rapidly than it decays whether the satellite is outbound or inbound rules out the possibility that the electrons are trapped for long periods of time on magnetic shells having fixed spatial relationship to the earth. The interpretation given to these observations is that the electron fluxes in the geomagnetic tail are impulsively injected into a region of space much more rapidly than the satellite moves through that region. In this view the short time constant referred to above represents the time required for the particle fluxes to build up at a fixed spatial point. Although the source cannot be specified from these observations, there are a number of possibilities. The energetic particles may be supplied by the closed portion of the magnetosphere; or, on the basis of recent discovery by Ness,[3] the impulsive source may be the neutral magnetic sheet in the interior of the geomagnetic tail. The decay of the electron flux is often roughly exponential, indicating that the electrons are escaping a source region, thereby depleting it. The short time constant may reflect an instability brought about by particle fluxes having energy density comparable to the energy density carried by the very weak magnetic fields in this region with kinetic energy. Such an instability is not at all unlikely considering the observed values of magnetic field[3] (as low as $5\ \gamma$) and particle flux (as high as $3 \times 10^7\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$ above 45 keV). To obtain the radial dependence of electron fluxes greater than 45 keV in the geomagnetic tail, use is made of the interpretation that the electrons occur at a given geocentric distance with a definite probability per unit time. It is therefore necessary to normalize the number of electron islands occurring in each interval of radial distance with respect to the velocity of the satellite. For example, the IMP-1 satellite takes 40 minutes to go from 10 to 11 earth radii, but over 300 minutes to go from 30 to 31 earth radii. The distribution formed in this way is given in Fig. 3 and shows that the frequency of injection of electrons into the tail falls off rapidly with increasing radial distance. Since the electron detector used in this study is a threshold device, the result could also be explained on the basis of an energy spectrum which softens with increasing radial distance.

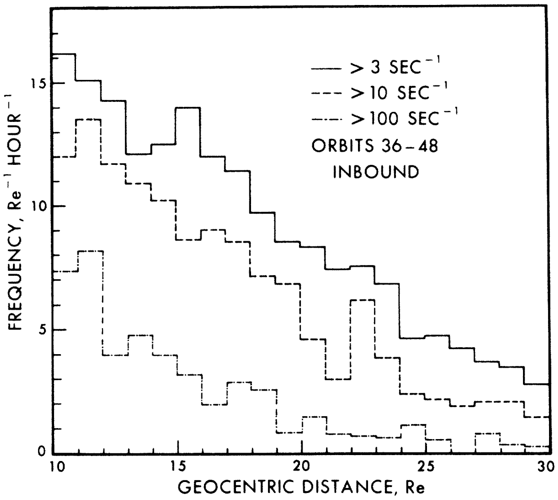

FIG. 3. The relative frequency of appearance of electron flux above 45 keV rapidly decreases with radial distance in the geomagnetic tail.

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