PHYSICAL REVIEW LETTERS

VOLUME 13 — 3 AUGUST 1964 — NUMBER 5

EVIDENCE FOR >30-keV ELECTRONS ACCELERATED IN THE SHOCK TRANSITION REGION BEYOND THE EARTH'S MAGNETOSPHERIC BOUNDARY*

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(Received 15 May 1964)

Since the solar wind is supersonic at the orbit of Earth[1] and carries with it an interplanetary magnetic field, it is expected to behave like a continuous fluid over dimensions comparable to the scale of the magnetosphere.[2] Conditions for a shock transition beyond the sunward side of the magnetosphere have been discussed over the past few years.[3-6] In this Letter we discuss measurements of electrons with energies >30 keV on the Explorer 18 (IMP-1) satellite.[7] We show that these electrons are confined to peaks less than 5000 km wide and trace out a region in space which is compatible with the expected location of the shock front[6] at a standoff distance of approximately 15 000 to 20 000 km beyond the boundary of the magnetosphere.

Recently Freeman, Van Allen, and Cahill[8] have reported high fluxes of electrons ($\sim 10^{10}$ cm^{-2} sec^{-1}) with a few keV energy throughout the region beyond the magnetosphere, and Freeman[9] has suggested that the outer limit of this region may coincide with a shock front. We show that the observed counting rate of our detector cannot be due to these low-energy electrons even for fluxes up to 10^{12} cm^{-2} sec^{-1} and point out that the high-energy electrons detected on Explorer 18 probably lie at the outer edge of the region containing the low-energy electrons found by Freeman et al.[8]

All the data we report here were obtained with the first gold-silicon surface-barrier charged-particle detector (D_1) of the University of Chicago cosmic-ray telescope. The telescope window was an aluminized Mylar foil which established a threshold energy of 30 keV for electrons and 800 keV for protons. A minimum energy loss of 160 keV was required to register a count. The geometrical factor was approximately 10 cm^2-sr.

After launch, Explorer 18 passed inward near the sun-earth (S-E) line and outward approximately 45° from the S-E line, drifting away from the line about 4° per orbital period. Figure 1 displays the counting rates versus geocentric distance. In Fig. 1(a) the magnetospheric boundary, as defined by the termination of the trapped radiation in the outer Van Allen belt, is located at 73 000 km. The flux of energetic particles which we shall identify as locally accelerated electrons is located at approximately 95 000 km with a peak width of about 2000 km. The counting rate of ~3 counts-sec^{-1} between this peak and the magnetospheric boundary is the same as in interplanetary space, and is due to cosmic-ray background.

Figure 1(b) represents measurements during a geomagnetic storm. The increase in counting rates in the interplanetary medium above the normal 3 counts-sec^{-1} arises from solar protons of energies from 1 to 30 MeV as determined by the cosmic-ray telescope measurements. The protons penetrate without attenuation the region between the electron peaks and the magnetospheric boundary. From Figs. 1(a) and 1(b), and more than 20 additional examples, it is clear that the

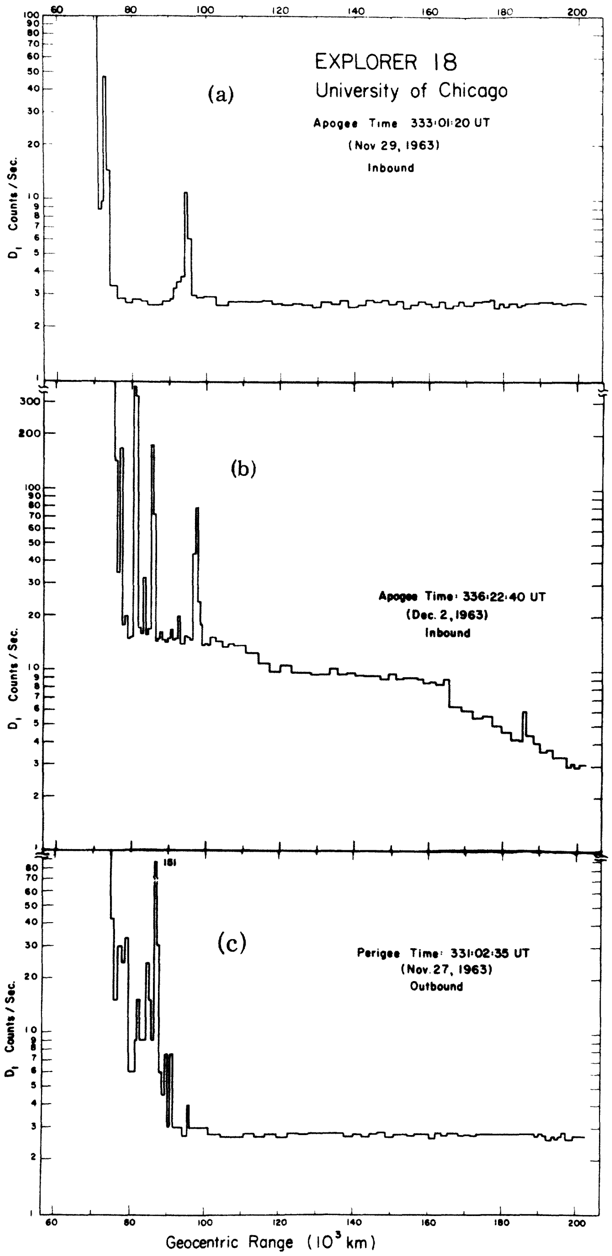

FIG. 1. (a) Intensity peak of electrons >30 keV at ~95 000 km on day 334 (orbit 1) which is associated with the shock transition region. The boundary of the magmetosphere is at 73 000 km. The peak which appears at the magnetospheric boundary is a common characteristic of the boundary. The background intensity between the magnetospheric boundary and the electron peak, and in interplanetary space is cosmic radiation. (b) Multiple peak structure separated by the prevailing flux level of cosmic radiation and solar protons on day 338 during a geomagnetic storm near the subsolar point (orbit 2). The increase of proton intensity with decreasing range is known to be a change of solar proton intensity with time. (c) Peak structure characteristic of observations at large sun-earth satellite angles.

counting rate in the regions between the electron peaks and the magnetospheric boundary is the same as the prevailing counting rate in interplanetary space. We attribute the existence of multiple peaks during the magnetic storm either to the rapid radial movement of the shock transition relative to the slowly moving satellite (~2 km-sec^{-1}), or to multiple shocks.

Figure 1(c) shows the multiple peak structure always found at large S-E-satellite angles.

By examining more than thirty-eight crossings of the shock transition we find that the peak widths shown in Fig. 1 are characteristic of all the data, namely the peak widths are all ~5000 km or less. This indicates that the particles at the peaks are electrons, since the lowest energy proton which could be detected by D_1 is 800 keV with a Larmor radius in this region at least ten times larger than the observed peak widths. Although rapid motion of the shock transition region with respect to the satellite could produce peaks which appear spuriously narrow, it is not likely that all the measurements over a three-month period could suffer this effect. In addition, the proton penetration of the peak region referred to in Fig. 1(b) proves that this region cannot trap protons of sufficient energy to be detected by our instrument.

To determine the detector response for these electrons several experiments were performed in our laboratory.[10] Since the detector window limits direct penetration of electrons to those with energies >30 keV, there are three cases to consider:

(1) Was the detector responding to the bremsstrahlung produced by electrons of energy less than 30 keV? We found that for electrons of energy just below 30 keV a flux of 10^{11} cm^{-2}-sec^{-1} is required to produce a counting rate of 10 per second. This flux in space is improbable since the energy density of such a flux exceeds by two orders of magnitude the solar wind energy density.

(2) Was the detector responding to electrons between 30 and 160 keV? We find that the counting rate in this energy range is due to pile-up of pulses within the resolving time of the electronic circuits. The counting rate depends strongly on electron energy. For example, a counting rate of 10 per second requires a laboratory beam of (a) 5×10^6 electrons cm^{-2}-sec^{-1} at 38 keV, or (b) 7×10^5 electrons cm^{-2}-sec^{-1} at 47 keV. Consequently, this pile-up effect above 30 keV could account for the observed range of peak counting

rates in space.

(3) Was the detector counting single electrons of energy >160 keV? The efficiency for counting individual electrons rises from zero at 160 keV to 0.6 at 230 keV and gradually declines to ~0.2 at higher energies. Thus, the possibility exists that some of the observed electrons were in this energy range.

All the evidence indicates that the particles producing the peaks are electrons of energies greater than 30 keV. It is clear that they could not be arriving and accumulating in peaks from interplanetary space with these energies, and these peaks are not the result of electrons continuously escaping from the magnetosphere as evidenced by the prevailing interplanetary flux levels observed between the magnetospheric boundary and the electron peak in Figs. 1(a) and 1(b). Therefore, we find no alternative but to explain these observations as the local acceleration of electrons to energies in excess of 30 keV at the shock transition.

By defining the shock transition as the location of the outermost of the observed electron peaks,[11] and by defining the magnetospheric boundary as coincident with the outer limit of Van Allen trapped particles,[12] we have plotted in Fig. 2 the instantaneous locations of the electron peaks from nineteen orbital periods which fall within 90° of the S-E line. The location of the transition region defined in this way is highly variable, both spatially and temporally, and may be unstable, especially at large S-E-satellite angles. However, there appears to be a persistent standoff distance of approximately 3 to 4 earth radii.

Preliminary data indicate that the flux levels in the electron peaks are highly correlated with the degree of disturbance of the geomagnetic field. For example, the multiple peak structure of enhanced intensities appears as in Fig. 1(b) during a geomagnetic storm. Otherwise, electron acceleration appears more or less continuous, and dependent on the strength of the solar wind. The amount of energy required for their acceleration above 30 keV is $<10^{-2}$ of the solar wind energy density.

It is unlikely that the magnetic fields in the vicinity of the transition region at the subsolar point are able to trap effectively these electrons for appreciable periods of time. Indeed, the evidence so far available suggests that they may escape away from this region along the shock

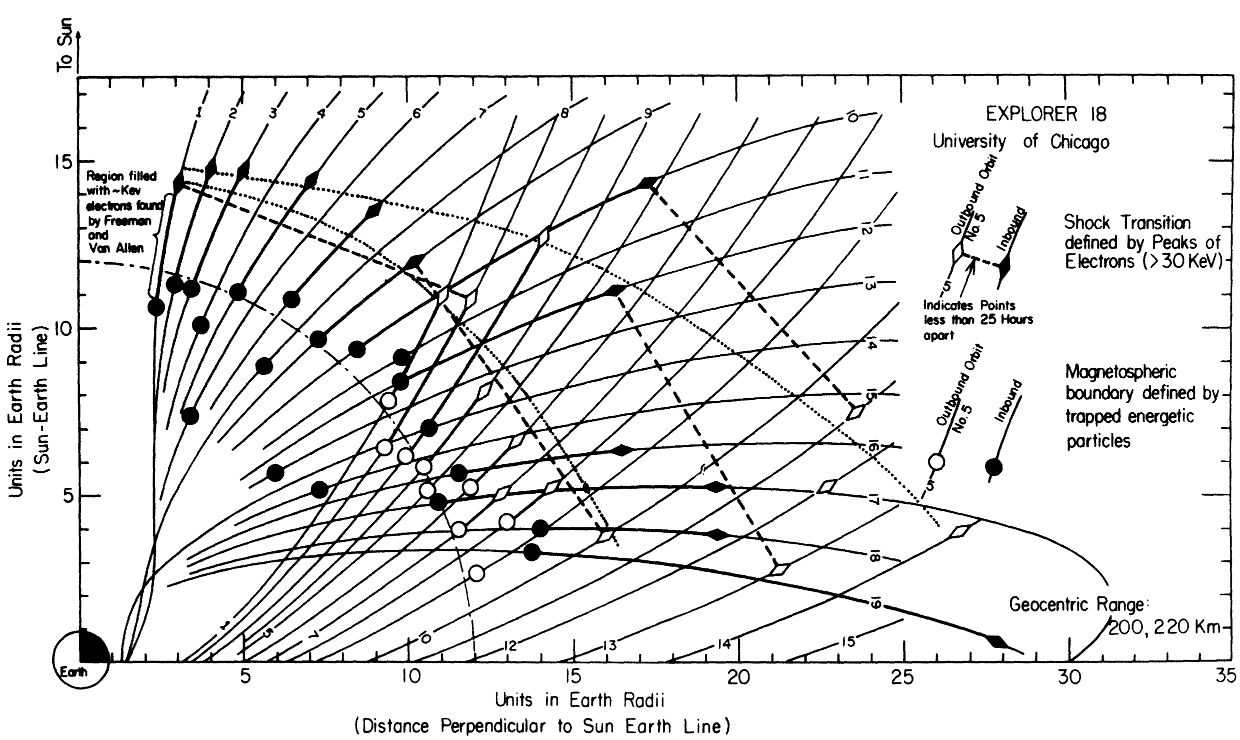

FIG. 2. Instantaneous positions of outermost electron peaks for 19 orbital periods. By defining the location of the shock transition with these peaks, the range of variability of the shock region is shown by the dotted lines. A dashed-line circular gradient is shown at 12 Earth radii to estimate the asymmetry of the magnetospheric boundary.

transition at increasing S-E-satellite angles —a possible interpretation of the multiple structure in Fig. 1(c). If so, they might enter the magnetospheric tail at very large angles with respect to the S-E line. Whether these electrons contribute to the electron population in the outer Van Allen belt is an interesting question.

By invoking the two-stream plasma instability, Kellogg[12] has suggested a plausible acceleration mechanism for electrons up to keV energies to explain the observations of Freeman et al.[8] A modification of this mechanism might provide the necessary accelerating fields to account for the >30-keV electrons.

In view of the detection of these electron peaks it is worthwhile examining earlier satellite data for their presence. Van Allen[13] now finds evidence for energetic electron peaks (>40 keV) in his Explorer-14 data, an example being the open-circle points in Fig. 2 of Frank, Van Allen, and Magagno.[14]

An electron detector designed by K. Anderson for energies greater than 40 keV was also on Explorer 18. A comparison of his results with those reported here will make it possible to determine the flux levels in the peaks.

We wish to emphasize the great variability of the region defined by electron peak distributions. This is a reasonable consequence of the continuously changing solar wind energy and flux, and the changes in interplanetary magnetic field intensity and direction relative to the S-E line. However, only the plasma probes and magnetometer results from Explorer 18 will reveal whether the conditions for a true shock transition exists or whether there is a broad disordered transition such as discussed recently by Bernstein et al.[15,16]

We wish to acknowledge the contributions of Mr. Remi Jacquet to the design and testing of the flight instrument. We also thank Mr. J. Lamport, Mr. J. Jezewsky, and the staff of the Laboratory of Applied Sciences of the University of Chicago for preparation of the prototype and flight instruments. We are especially grateful to Mr. P. Butler, Dr. F. McDonald, and Mr. R. Martin and their staffs at the Goddard Space Flight Center for their efforts in preparing the Explorer-18 satellite. Through the supervision of initial data tapes by Dr. N. Ness, we have had access to our data much earlier than would otherwise be possible. For our data reduction we thank Mr. G. Lentz, Mr. L. Littleton, and Mr. M. Case.

*This research was supported in part by the National Aeronautics and Space Administration under Grant No. NASA-NsG-179-61 and Contract No. NAS-5-2990, and by the U. S. Air Force Office of Scientific Research, Grant No. AF-AFOSR-521-64.

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[10]We are particularly indebted to Professor S. K. Allison for the use of his laboratory facilities to set up the electron accelerator and to Dr. M. Garcia-Munoz for his help in determining the electron response of the IMP-1 detectors. We thank Dr. S. B. Burson and Dr. E. B. Shera of Argonne National Laboratory for their assistance in determining the sensitivity for electrons of energy above 160 keV with their beta-ray spectrometer.

[11]More precisely, we define this peak position for the shock transition as the outermost peak of that distribution of peaks which are individually separated by the prevailing interplanetary flux level; two such base levels are illustrated in Figs. 1(a) and 1(b). Except for periods of unusually disturbed magnetic conditions, when isolated peaks sometimes appear at great distances, no additional electron peaks are found between the defined transition peak and the apogee of the satellite. The outer limit of the trapped radiation is recognized by a drop in intensity of many orders of magnitude but generally not reaching the interplanetary flux level until after the appearance of a narrow intensity peak [such as shown in Fig. 1(a) at 73 000 km]. We define this peak as the boundary of the magnetosphere, but we do not discuss here the origin of this magnetospheric-associated peak.

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