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ACCELERATION OF ELECTRONS NEAR THE EARTH'S BOW SHOCK*

J. R. Jokipii† and Leverett Davis, Jr.
California Institute of Technology, Pasadena, California

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Recent observations by Fan, Gloeckler, and Simpson,[1] and Anderson, Harris, and Paoli,[2] using IMP-1, have done much to reveal the nature of the pulses of 30- to 50-keV (or higher) electrons observed in the region of the outer magnetosphere.[3,4,5] The observations of Fan et al.[1] show pulses having counting rates of the order of 10 times background which last only a few minutes, corresponding to the passage of the satellite through regions about 2000 km thick if they are stationary with respect to the earth. However, the nonlinear response of their detector may have obscured the true nature of the pulses. Fan, Gloeckler, and Simpson[1] were the first to emphasize that electrons are accelerated and occur in a thin region at the bow shock outside of the magnetosphere, locating the bow shock at the outermost point where electrons are observed on each orbit, whereas Anderson, Harris, and Paoli[2] consider the electrons to be of magnetospheric origin. In this Letter we conclude that a model interpreting the pulses as thin layers, with the outermost layer usually being at the bow shock, is unlikely on both theoretical and observational grounds. We find that electrons are found beyond the bow shock and consider two promising models of the phenomenon.

Any >30-keV electrons must drift through the magnetic field with the bulk velocity of the solar wind. They also spiral rapidly (>10^{10} cm/sec) along the lines of force. Thus a few thousand kilometers behind the shock the flux of energetic electrons, in the model of Fan, Gloeckler, and Simpson,[1] should be essentially the same as in the shock, the electrons having been convected away from the shock by the wind or having flowed along the lines of force that lead through the shock. If 1- or 2-keV electrons would explain the observations, it could be argued that they are both accelerated and then decelerated in the shock structure, as in the solitary wave of Adlam and Allen,[6] or Davis, Lüst, and Schlüter.[7] But apparently the only way to accelerate electrons to >30 keV in a stationary shock is by stochastic processes, and these cannot be reversed to decelerate the electrons behind the shock.

Consideration of these arguments led us to compare carefully Fig. 2 of Fan, Gloeckler, and Simpson,[1] which shows the locations of the electron pulses they interpret as being at the shock front, with the corresponding figures for the IMP-1 magnetometer and plasma results of Ness, Scearce, and Seek,[8] and Bridge, Egidi, Lazarus, Lyon, and Jacobson.[9] It appears that the plasma and magnetic-field data agree well on the location of the shock, but that the outermost high-energy electron fluxes are usually a few earth radii outside the shock, on one occasion at least six earth radii outside, and on a few occasions are seen only inside the shock if at all. Except for one disturbed period when the cosmic-ray background was high and they detected pulses of electrons far outside the shock, the observations of Anderson, Harris, and Paoli,[2] which show pulses at energies above 45 keV with fluxes of 10^4-10^6 cm^{-2} sec^{-1} on a background of about 7×10^3 cm^{-2} sec^{-1}, appear to be consistent with this picture, although we have not made a detailed comparison of their results with those of Fan, Gloeckler, and Simpson.[1]

We therefore suggest that rather than interpreting the structures where electrons are found as thin layers which are traversed on most passages of the space craft, they be interpreted as regions much more transient in time and much more extended in space. They should occur typically every hour or so, lasting a few minutes and blowing away with the solar wind. A wind velocity of 400 km/sec will move them 10^5 km, or about the radius of the shock surface, in 4 minutes. Since IMP-1 spent long periods well outside the shock front, during which no energetic electrons were seen (except for one storm period), it appears that bow-shock-associated electrons are confined to a region that rarely, if ever, extends more than a few earth radii outside the shock front. Between the shock and the magnetopause, pulses were observed much more often when far from the subsolar point than when near it. This suggests that the layer of energetic electrons may, on different occasions, have its upwind edge at various distances from the subsolar point. The solar wind extends the regions downwind into the region behind the shock. Thus, far from the subsolar point, several such regions are likely to sweep past during one passage of the satellite, while nearer the subsolar point it is more likely that only one occurs.

Consider now possible explanations both of the occasional presence of energetic electrons and the fact that they tend not to be observed more than a few earth radii outside the shock. Excluding from this discussion implausible mechanisms involving Mach 20-30 nonlinear waves propagating outward from the shock,[10] which accelerate electrons and protons to high energies and then decelerate them as part of the wave structure, and mechanisms producing semipermanent thin layers in the region downwind from certain unusual tubes of force in which electrons are accelerated, we note two models that seem to merit serious consideration. They are depicted schematically in Fig. 1.

It may be that electrons with energies well above 30 keV are either always or occasionally produced in or behind the shock, perhaps as a nonexponential tail to a few-keV Boltzmann distribution expected there and supported by the observations of Freeman, Van Allen, and Cahill.[11] The source may be located anywhere behind or near the shock, so long as electrons may leak out in front of the shock layer along lines of force. If the density of these particles at the shock, and hence their flux out, is low, they will ordinarily not be observable. But if from time to time the interplanetary field were to become more irregular than usual, or developed a precursor as suggested by Ness, Scearce, and Seek,[8] the electrons may mirror and become temporarily trapped in front of the shock. The local density will build up to a value limited by slow diffusion along the field and by the sweeping away of the entire structure by the solar wind. If this trapping raises the flux of 50-keV electrons to 10^5 cm^{-2} sec^{-1}, i.e., about 10^{-4} of the flux expected for 1-keV electrons behind the shock, the observations would be explained. Alternatively, of course, the field fluctuations could be continually present to provide the confinement to regions near the shock, but the source could be intermittent. The rms variations in the field found

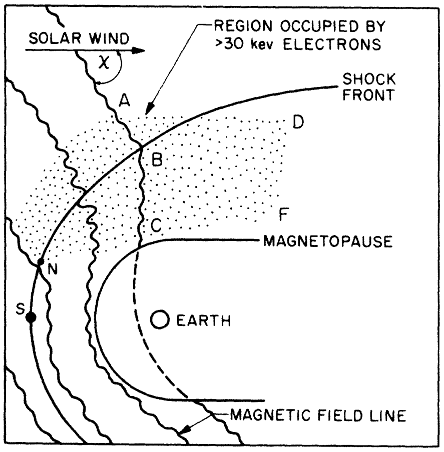

FIG. 1. Schematic representation. In model 1, acceleration occurs either along NB or in region NBC. In model 2, the particles are accelerated in NAB and possibly in NBC. Boundaries NAD and NCF will not be sharp because of diffusion along field lines. N can occur at various distances from S, the subsolar point. The solar wind blows accelerated particles into the region ABCFD and beyond. When trapping or acceleration ceases, the whole region drifts downwind.

by Ness, Scearce, and Seek[8] both inside and, at times, outside the shock, and the very short period fluctuations observed by Pioneer I,[12] suggest that at times the field may contain irregularities that serve as mirror points and occasional weak shocks that can change the pitch angles of the electrons. If these produce a diffusion length of the order of 10^9 cm along lines of force, the confinement to a thin layer outside the shock would be explained. Since Ness, Scearce, and Seek[8] find larger rms fluctuations behind the shock, the diffusion length there should be shorter. Because these irregularities (sausages closed off by mirror points) may become filled with energetic electrons near the shock and then be convected away by the wind, the thickness of the region behind the shock should increase downwind from its leading edge. Fermi acceleration in this region may be a factor in both this and the following models.

A variant of this is sufficiently attractive that we would like to regard it as a distinct second model. The absence of electrons more than a few radii outside the shock seems to require mirror points, moving with the solar wind, which reflect the outward-moving electrons back toward the shock. Irregularities in and just behind the shock and the enhanced field strength at the shock should scatter electrons back out into the wind. These electrons, reflecting back and forth between the mirror points and the shock, are accelerated by a first-order Fermi process. Each time they are reflected by a mirror point in the wind, the electrons receive a velocity increment $2v_w \cos\chi$, where $\vec{v}_w$ is the wind velocity and χ is the angle between the wind velocity and $\pm\vec{B}_0$, the magnetic field outside the shock. More precisely, if $\vec{n}$ is the outward-directed normal to the shock front, $\cos\chi = -(\vec{B}_0 \cdot \vec{v}_w)(\vec{B}_0 \cdot \vec{n})/B_0 v_w |\vec{B}_0 \cdot \vec{n}|$. Assume that some of the ~1-keV electrons found behind and in the shock[11] leak out ahead of the shock along the field lines and are accelerated. For a nominal $2v_w \cos\chi = 5\times10^7$ cm/sec, it takes of the order of 200 reflections to accelerate them to 50 keV. The trapping must therefore be quite efficient; about 90-95% of the electrons approaching the mirror points must be reflected to produce the requisite fluxes. Also, in order to keep the pitch angles of the electrons from decreasing as they gain energy, a plausible model requires efficient randomization of pitch angles by shocks or magnetic irregularities. The time available to accelerate the particles is the time a field line takes to cross a region the size of the magnetosphere, or about 10^2 seconds, unless the interplanetary field is precisely parallel to the solar wind velocity. Since particles must mirror many times to gain energy, this limits the distance from the shock at which acceleration can proceed. This limit is of the order of 10^9 cm for 1-keV electrons, in excellent agreement with the observed cutoff at a few earth radii.

We suggest that a mechanism similar to this, which we are exploring in more detail, may accelerate particles in other situations where a plasma containing a fluctuating magnetic field flows through a shock with high Mach number.

Since the region outside the shock that is filled with energetic electrons depends on the direction of the field outside the shock, and the effectiveness of the trapping and accelerating mechanism depends on the kind of magnetic irregularities present, intercomparison of the energetic electron and magnetometer observations should provide many obvious tests of these models.

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[†] National Science Foundation Predoctoral Fellow.

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