On the Physical Origin of Outer Radiation Belt 1–10 MeV Electrons

R. B. Sheldon, H. E. Spence, J. D. Sullivan, T. A. Fritz and Jiasheng Chen

Boston University, Boston, Massachusetts

Abstract

We report on the POLAR/CEPPAD discovery of a trapped, $60° < \theta < 120°$ pitch angle electron population in the outer cusp (8–11 Re), whose energetic electron component extends from ~2 MeV down to at least 30 kev. We have carried out test particle simulations using the Tsyganenko 1996 model (T96) to demonstrate theoretically the trapping of these energy electrons in the outer cusp region and the resonant frequencies of its trapped motion. We argue that the large phase space densities observed there are sufficient to fill the outer radiation belts with 1–10 MeV, "killer", electrons. Yet despite the ~40 years of work since the discovery of the outer radiation belts, the origin of these electrons is still unknown. During the equinoxes, the POLAR orbit passed through the outer cusp as well as the radiation belts, and observed increases in the trapped cusp electrons which preceded the occurrence of large fluxes of these electrons at geosynchronous altitude. Since electromagnetic fluctuations of the appropriate resonant frequency and power adequate to pump up the energy of such a trapped population are known to exist in the cusp region, the cusp may possibly be the birthplace of outer radiation belt electrons.

Introduction

"Killer" electrons, the 1–10 MeV electrons which define the outer radiation belt, are a significant environmental hazard to geosynchronous satellites, yet the origin and prediction of these electrons remains a mystery [*Baker et al.*(1997)]. Weak statistical links ([*Blake et al.*(1997)]) or neural net "black boxes" [*Koons and Gorney*(1991)] are all we have found in the ~40 years since their accidental discovery by Van Allen [1959] . What has been lacking are physical models that direct the statistical investigation into fruitful correlations that might create better predictors of MeV electron enhancements.

Where are these electrons and why is their origin a mystery? These MeV electrons are trapped in the Earth's dipole field, at a radial distance from ~ 3–7 Re at the equator, forming the outer radiation belt. As the Earth's dipole field weakens at larger distances, the fluctuations of the field caused by solar wind disturbances become increasingly important, so that the radial transport rate is faster than one Re per day at distances beyond 6 Re [*Schulz and Lanzerotti*(1974)]. Beyond 8 Re, the dipole field is so distorted that it cannot trap the electrons at all, that is, they do not possess all three adiabatic invariants of the motion and therefore are at best "pseudo-trapped" [*Roederer*(1970)]. Generally it is the third invariant that is violated most easily, meaning that the electrons cannot drift 360° around the Earth without encountering the magnetopause and becoming lost. Thus if the source of the electrons is not in the trapping region itself, it would appear to be a transient in the outer regions, having a lifetime of several tens of minutes, the time it takes for electrons to drift around the Earth. Yet extensive searches in the trapping region have shown no acceleration region or population that can be the source of killer electrons (e.g., a "Nishida recirculation" type mechanism [*Ingraham et al.*(1996); *Paulikas and Blake*(1979); *Nishida*(1976)]).

Recent work using POLAR has confirmed what other data sets have been telling us, that the phase space density at constant magnetic moment uniformly rises toward higher L-shells, away from the Earth [*Selesnick and Blake*(1997)]. Since the diffusive radial transport rate for these electrons is rapid, this suggests that the source is external to the trapping region. However, the solar wind (at infinite L-shell) has a lower phase space density than the magnetosphere whether we compare at constant energy or constant magnetic moment [*Li et al.*(1997)]. Thus until recently we could only say that the mysterious source of these electrons lies at $10 < L < \infty$. This is troubling, because these L-shells hold pseudo-trapped populations and should have lower, not higher, phase space densities than the trapped population, unless one found a source, an extremely rapid acceleration mechanism that could accelerate in less than a drift period (e.g., the 1991 "shock acceleration" event [*Li et al.*(1993)]), yet remain for many hours while filling the radiation belts.

Another, previously unexamined possibility exists, that there may be a trapped population at large L-shells whose trapping does not depend on the usual dipolar magnetic bottle geometry. If this population exists, it could account for the greater phase space density seen at higher L-shells as well as provide a location for slow, steady acceleration to occur. And that is what we have found. The recent discovery of energetic electrons quasi-trapped in the cusp has provided a fortuitous glimpse of what we believe to be a suitable birthplace of these killer electrons, which then populate the outer radiation belts.

Data Analysis

POLAR is in a 2 × 9 Re orbit that on October 14, 1996, passed through the nominal outer cusp before traversing the radiation belts. The outer cusp is defined to be a region inside and adjacent to the magnetopause (8–10 Re), with noticeably reduced magnetic field strengths, having broadband wave power, and generally within some radial distance (2–3 Re) of the topological minimum B point. We do not define the outer cusp with respect to a particle population for the same reason that the plasmasphere, radiation belts, and ring current define overlapping regions in the dipole magnetosphere. We observe a trapped electron population in the outer cusp on this orbit, generally during the two seasons per year when the POLAR orbit precesses through this region. Data from TIMAS and HYDRA on this day show that the magnetopause was first crossed at 0100, at which time EFI showed an abrupt increase in broadband noise. HYDRA showed brief bursts of sheath electrons between 0100–0230 that appeared to be anti-correlated with IES and HIST trapped electrons. These short magnetopause crossings ceased by 0230 along with most of the EFI wave power.

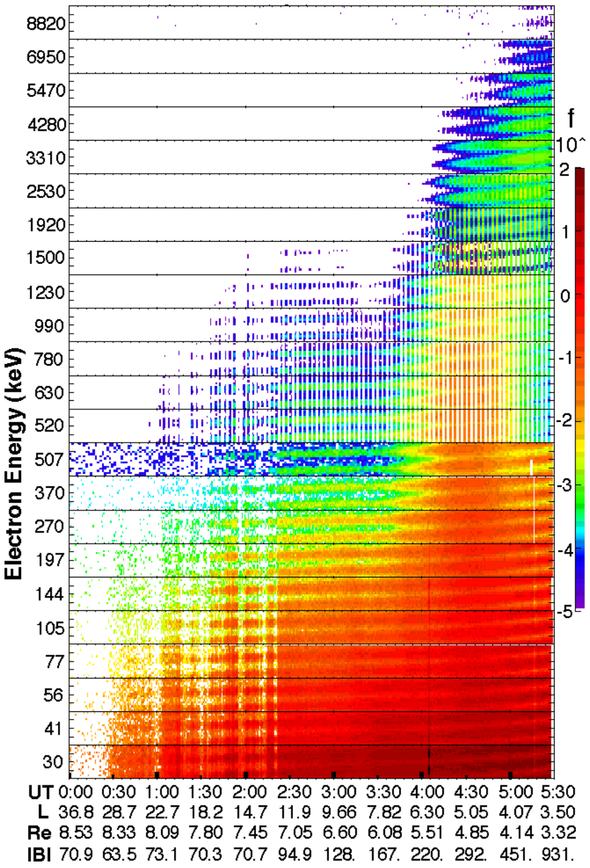
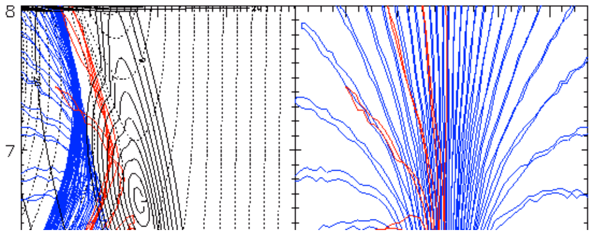


Figure 1. Electrons trapped in the cusp observed by POLAR. See text for details.

In Figure 1 we plot time/energy/roll-angle spectrograms of phase space density from the CEPPAD/HIST and CEPPAD/IES electron instrument [*Blake et al.*(1995); *Contos*(1997)] on the POLAR spacecraft. The vertical stripes in the upper panels are an instrument artifact caused by mode switching of the HIST telescope. Successive panels are logarithmically spaced in energy where each panel displays the roll modulation (pitch angle) of the particles; the fluxes are clearly peaked around 90°. The color scale displays the logarithm of f (s^3/km^6) from 0.00001 (purple) to 100 (red). The left half of the plot shows 30–1000 keV electrons with quasi-trapped pitch angle distributions located in the outer cusp at $L>10$. The right half of the plot is an outer radiation belt traversal. Comparing the radiation belt and cusp loss cones, we see that the cusp's is much wider and the fluxes more isotropic, which is characteristic of a "leaky magnetic bottle". It also appears that the wide loss cone of the cusp is filled at a very low, isotropic level. Comparing the phase space densities at equal magnetic moment (kev/nT), which involves connecting the two regions by a diagonal line roughly parallel to the isodensity contours of the radiation belts, reveals that the outer cusp has higher densities than the outer radiation belts, allowing the possibility of inward diffusion at constant first invariant. Note that the radiation belt pass is at high latitude so that the electron flux would map into the wide loss cones of the outer cusp, suggesting that the second invariant is not conserved if the cusp is the source of these electrons.

Simulations

Now this quasi-trapped cusp population is highly unusual because, classically speaking, the cusp cannot trap particles [*Roederer*(1970)], it is not an "excluded region" in the Störmer theory of an idealized dipole [*Störmer*(1911); *Rossi and Olbert*(1970)]. However, the interaction of a magnetic dipole with the solar wind modifies the topology in a fundamental way that has not been adequately considered in the theory of trapped particles; rather than a dipole, the cusp appears to be quadrupolar. We demonstrate the existence of this particle trap using the somewhat extreme geomagnetic conditions of a nearly minimum latitude cusp and a high speed solar wind (figure 2).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