The Electron Radiation Belt

Xinlin Li
Laboratory for Atmospheric and Space Physics, U. of Colorado, Boulder, USA

Michael A. Temerin
Space Sciences Laboratory, U. of California, Berkeley, USA

February 29, 2000

Abstract. Electron radiation belts can change dramatically in a few seconds or slowly over years. Important issues in understanding such changes are: 1) What is the source of electrons in the radiation belts? 2) How important is radial diffusion compared to other radial transport mechanisms? 3) What are the detailed changes in the magnetosphere that produce radial diffusion? 4) Why is the response of the electron radiation belt to changes in the solar wind different from that of substorms and of the ring current? 5) Are processes other than radial transport, such as wave-particle interactions, important in energizing electrons in the radiation belts?

Keywords: radiation belt, relativistic electrons, energization, transport, loss

1. Introduction

An electron radiation belt is a population of energetic electrons trapped on fairly stable orbits within a magnetosphere's magnetic field. Earth's electron radiation belt is usually divided into the inner belt, centered near 1.5 Earth radii (R_E) from the center of the Earth when measured in the equatorial plane, and the outer radiation belt which is most intense between 4 and 5 R_E. The 'slot' region separates the two radiation belts. Such a description gives a false impression of permanence. In fact, the electron radiation belts are constantly decaying and episodically reforming and each reformed belt may have an extent, center location, and intensity different from its predecessor. There is also a inner radiation belt region, L=1.2-2.5, consisting of energetic protons ($>$100 MeV), which are stable over scales of the solar cycle or longer. This belt is thought to be produced by the CRAND (comic ray albedo neutron decay) process, that is, it is due to neutrons, produced by the interaction of cosmic rays with the atmosphere, that decay to protons. This decay also produces an energetic electron but the process is far too weak to produce the electron belts.

The main question concerning the electron radiation belts is why do they exist at all. Electrons within Earth's magnetosphere come from two main sources: the solar wind and the ionosphere. The typical temperature of electrons in the ionosphere is less than 1 eV and the typical temperature of solar wind electrons is about 10 eV. Yet the Earth has radiation belts whose elec-

© 2003 *Kluwer Academic Publishers. Printed in the Netherlands.*

trons range in energy from 400 keV (a somewhat arbitrary lower limit to be considered a radiation belt electron) to above 15 MeV. How these electrons come to be energized is the main theme of radiation belt research. The acceleration of charged particles is also of cosmic significance. From pulsars to galaxy clusters, magnetic fields pervade the universe and trap energetic particles. Much of what we know of the universe comes from energetic particles, mostly through their local interactions that produce gamma-rays, X-rays, and radio emissions. The study of charged energetic particles in magnetic and electric fields thus provides a unifying theme over a vast range of scales.

The motion of charged particles in magnetic and electric fields is well known in principle and can be calculated from the Lorentz force law. These calculations show that charged particles can be trapped by magnetic fields. In a quasi-dipole magnetic field such as that of the Earth, trapped particles conduct three distinctive motions: gyration, bounce, and drift. Electrons drift eastward around the Earth as they bounce between the stronger magnetic fields in the northern and southern hemispheres and gyrate around the local magnetic field. More energetic particles bounce and drift faster. These three motions usually have well separated time scales. For example, for an 1 MeV electron with an equatorial pitch angle of 60° at r=6 R_E, the gyration, bounce, and drift periods are about 10^{-3}, 10^0, and 10^3 seconds, respectively.

There is an adiabatic invariant associated with each of these motions. As long as the magnetic field changes slowly over the respective time-scale, the corresponding invariant remains constant (Northrop, 1963). The conservation and violation of these invariants is central to understanding the energization and loss of electrons in the radiation belts. The first invariant is proportional to the magnetic flux within a gyro orbit; the second invariant is proportional to the magnetic field integrated along the bounce orbit; and the third invariant is proportional to the magnetic flux within the drift orbit. The energy of a particle increases for the same first and second adiabatic invariants as a particle moves inward into stronger magnetic fields which violates the third adiabatic invariant. Such violations can occur if the magnetosphere within the drift orbit fluctuates on a time scale of the drift orbit. Thus energization will occur if a particle moves inward while preserving its first and second adiabatic invariants. Actually the first and second adiabatic invariants are sometimes violated by waves that scatter particles in pitch angle. But pitch-angle scattering often nearly conserves energy. Thus a particle, even though it may not conserve its first and second adiabatic invariants, will still gain energy as it moves inward into stronger magnetic fields. Pitch-angle scattering can also scatter particles onto orbits that intersect the atmosphere resulting in loss of particles from the radiation belts.

After the discovery of the radiation belts at the beginning of the space era, an impressive amount of research was done during the 1960's and early 1970's. Models of the average properties of the radiation belts, such as AE-8

model (Vette, 1991) were developed; radial diffusion was established as the dominant energization and radial transport mechanism (Schulz and Lanzerotti, 1974); and wave-particle interactions were established as an important loss mechanism responsible, in part, for the slot region (Lyons et al., 1972). By the end of 1970's, radiation belt research had mostly moved from Earth to Jupiter and the other major planets. The Pioneer and Voyager missions revealed that all of the major planets, Jupiter, Saturn, Uranus, Neptune, have well developed magnetospheres and trapped radiation belts. The Jovian trapped radiation is the strongest. The other three planets have radiation belts comparable in intensity to Earth.

Research into the radiation belts of the Earth was revived by the startling and detailed results from the CRRES satellite, which gathered data in the years 1990-1991. CRRES had a geosynchronous transfer orbit in the equatorial plane with a period of 10 hours ideal for investigating the radiation belts. Figure 1 shows electron differential fluxes as a function of time and L, measured by the CRRES/MEA instrument (Vampola et al., 1992) and the corresponding geomagnetic indices for the whole CRRES period. The data are characterized by abrupt electron enhancements and decreases extending across L-values from L$\sim$2 to $\sim$7. All energies often rise and fall coherently but lower energy electrons show more frequent variation, associated with substorms as indicated by AE, while higher energies vary more with geomagnetic storms as indicated by Dst. All the CRRES/MEA channels can be contaminated by penetrating energetic protons ($>$100 MeV) and highly relativistic electrons ($>$5 MeV). This contamination is most evident in the inner belt region where it's due to penetrating inner belt ions and in the slot region after March 24, 1991 (day number 448 and orbit number 587). The 'contamination' after March 24 is due to a new electron belt of $>$13 MeV electrons that formed in less than one minute. The CRRES satellite was fortunate to be able to see directly the formation of this belt. On March 24, 1991, as the CRRES satellite moved toward perigee, it measured the injection of greater than 13 MeV electrons as illustrated in the left column of Figure 2 (Blake et al., 1992). The subsequent peaks are drift echoes due to the reappearance of the electrons after a complete drift around the Earth. The differences in the count rates of the different energy channels shown in Figure 2 are due solely to differences in the detector's respective geometric factors, indicating that nearly all injected electrons were above 13 MeV in energy.

The injection can be traced back to the Sun. Activity on the sun about a day before resulted in a fast interplanetary shock traveling $>$1400 km/s. The shock compressed the magnetosphere and produced an inductive electric field which energized electrons by bringing pre-existing $\sim$1-2 MeV electrons from L$\sim$8 to L$\sim$2.5 as shown by the test particle simulation (right column in Figure 2) that Li et al. [1993] used to model successfully the effects of this shock. This simulation used an analytical model of the electric and magnetic

fields produced by the interplanetary shock . Later Hudson et al. [1997] used fields generated by global MHD simulations to get similar results.

As can be seen from Figure 1, the >13 MeV electron belt lasted until the end of the CRRES mission. Subsequently the belt was detected by the SAMPEX satellite and, as can be seen from Figure 3, traces of the belt still remain (year 2000) while the belt slowly decays and diffuses inward. Thus an electron radiation belt, formed in less than a minute, has lasted nearly a decade. The creation of this electron radiation belt did not fit the dominant model (radial diffusion) that had been thought to explain the evolution of radiation belts nor was it clear whether the other abrupt electron enhancements seen in Figure 1 were best explained by radial diffusion acting much faster during magnetic storms or whether such enhancements could be better explained by injections like the one that created the March 24 belt or some other fast process. On the other hand recent data have also confirmed predictions of the radial diffusion theory. The slow inward radial motion of the >13 MeV electrons seen in Figure 3 is consistent with radial diffusion theory (Schulz and Lanzerotti, 1974) as are changes seen in the outer radiation belt by the Polar satellite during quiet times and recently modeled by Selesnick et al [1997]. These considerations have led to some **rethinking** of radiation belt dynamics.

2. Understanding the Electron Radiation Belts

2.1. Source of electrons in the radiation belts

The energy that can be gained by radial transport, whether in the form of radial diffusion or fast injections, through the violation of the third adiabatic invariant is limited by the ratio of the magnetic field magnitudes within the region of radial transport. Thus radial transport as an energization mechanism through the violation of the third adiabatic invariant normally requires a source population of electrons that is already hot compared to the average temperature of electrons in the possible sources: the solar wind (Te$\sim$10 eV), the magnetosheath (Te$\sim$30 eV), the central plasmasheet (Te$\sim$500-2000 eV), or the ionosphere (<1 eV).

Though the average temperature of solar wind electrons is relatively small (Te$\sim$10 eV) the solar wind also contains a much hotter ‘halo’ and an even hotter ‘superhalo’ population of electrons (Lin, 1998). This ‘superhalo’ population varies with solar and solar wind activity and has a temperature (Te$\sim$5 keV) whose high energy tail is conceivably sufficient to produce some of the electrons in the radiation belt if energized within the magnetosphere solely by radial transport. However, recently Li et al. [1997a] examined this hot ‘superhalo’ population and showed that it did not have sufficient phase space density

to supply the radiation belts without additional heating processes within the magnetosphere. This result implies that the source population for the electron radiation belts must be created within the magnetosphere.

Various mechanisms have been suggested for creating the source population of electrons on which radial transport may act to produce the radiation belts. Some of these possible mechanisms and source regions are reconnection in the magnetotail, additional heating within the magnetotail, heating within the cusp region (Sheldon et al., 1998), or the acceleration of ionospheric electrons out of the auroral zone into the outer magnetosphere. Reconnection in the magnetotail may be important not only because reconnection may accelerate electrons directly but also because it takes place in regions of weak magnetic fields favorable for further acceleration through conservation of the first two adiabatic invariants or through generation of waves that may heat electrons by violating their first adiabatic invariant near the reconnection region. Recent FAST satellite data have also shown that parallel electric fields and related wave turbulence in the auroral acceleration region can heat ionospheric electrons to keV energies and inject them into the magnetosphere (Carlson et al., 1998). In any case, the normal population of electrons in the plasmasheet is characterized by a Kappa distribution which has a high energy tail compared to a Maxwellian distribution. It is not known how such distributions are formed (though the above mentioned mechanisms are possibilities) and though it appears that the phase space density of the average Kappa distribution in the current sheet of the magnetotail has sufficient phase space density to be the source of the electron radiation belt it is not as clear that these electrons can be transported inward efficiently enough.

Thus electron phase densities and heating mechanisms in the outer magnetosphere are important unresolved issues whose eventual resolution will tell us whether the outer magnetosphere is the source region for the electron radiation belts.

2.2. Mechanisms of radial transport mechanisms

The classic mechanism for forming the electron radiation belts, given a sufficient source population in the outer magnetosphere, is radial diffusion. Radial diffusion was thought to proceed slowly but CRRES, SAMPEX (Baker et al., 1994), Polar (Selesnick and Blake, 1997), and multiple satellite data (Li et al., 1997b; Reeves et al., 1998) have confirmed that much of the variation occurs quickly during magnetic storms. The question is whether these variations are best described by radial diffusion acting much more quickly during magnetic storms or whether these variations are best described by a single event like on March 24, 1991 or another heating process. The formulation of radial transport as radial diffusion makes sense if change in the fluxes of radiation belt electrons are slow on the time scale of the drift period. In the case of

the March 24, 1991 event, the radiation belt formed in less than one drift period and so radial diffusion is not a good description of the process. During most magnetic storms the typical pattern of energetic electron flux changes is different. Typically, the relativistic electron flux drops rapidly during the main phase of the storm. The electron flux stops decreasing as Dst reaches its minimum and then in few hours, as Dst recovers, the electron flux increases and usually reaches values larger than before the storm. The reformation of the radiation belts during the recovery phase of magnetic storms thus seems to occur on an intermediate scale of hours. So the increase during a drift period ($\sim$10–20 minutes for 0.4–1 MeV electrons in the outer zone) is not small but neither does most of the increase occur in less than one drift period. Complicating the above analysis is that much of the decrease in the electron flux during a storm and some of the increase is due to a fully adiabatic response (conserving all three adiabatic invariants) of the radiation belt electrons to the change in the magnetic field as indicated by the Dst index (Li et al., 1997b; Kim and Chan, 1997). Unfortunately to take into account properly the adiabatic response, which in principle is understood, we need to know the total magnetic field response so as to calculate the magnetic flux within the drift orbit for which Dst gives but a poor proxy.

2.3. Detailed mechanisms of radial diffusion

The basic idea of the radial diffusion formulation, as of other diffusion formulations, is that the individual fluctuations that produce the diffusion can be ignored and only their average properties need be considered. But this need not hinder us from looking into details and asking about the individual fluctuations that drive radial diffusion. To be effective in producing radial transport, radial diffusion requires that there be variations in the electric or magnetic fields within the magnetosphere on a time scale of a drift period. Such variations can be due to pressure pulses in the solar wind, to ULF waves generated at the magnetopause or within the magnetosphere, or to changes in the electric and magnetic fields driven by substorms and magnetic storms. Recently Baker et al. [1998] and Elkington et al. [1999] have argued that specific ULF waves are important in driving radial diffusion. Elkington et al. [1999] have been able to use MHD simulations to determine the response of the magnetosphere to the solar wind and to use test particle simulations to determine the response of the radiation belt electrons to such magnetospheric changes. Thus they were able to produce radial diffusion using the actual details of the electric and magnetic field fluctuations. Rowland and Wygant [1998] have shown on the basis of CRRES electric field data that during magnetic storms large electric fields penetrate deep into the magnetosphere. Such fields must be important in creating the ring current but their effects in creating the electron radiation belts have not been specifically analyzed.

2.4. Electron radiation belt response to the solar wind

Paulikas and Blake [1979] showed that there is a very good correlation between the solar wind velocity and the MeV electron flux at geosynchronous orbit. Since geomagnetic activity and substorms are known to be controlled more strongly by the polarity of the interplanetary magnetic field, the better correlation of the radiation belt electrons with solar wind velocity is mysterious.

Recently we have reexamined this issue using several years of almost continuous solar wind data from the Wind satellite and confirmed the results of Paulikas and Blake [1979]. We also found that velocity fluctuations in the solar wind are strongly correlated with the velocity itself (see Figure 4 for an an example of this correlation). Perhaps such velocity fluctuations in the solar wind drive radial diffusion and thus can explain this correlation. Larger solar wind velocities may also drive fluctuations at the magnetopause, perhaps through the Kelvin-Helmholtz instability, which may produce ULF waves within the magnetosphere. Currently we know that there is a good correlation between the solar wind and radiation belt electrons but we do not know the physical mechanism that produces this correlation.

2.5. Wave-particle interactions as an energization process

Wave-particle interactions are thought to be important in precipitating electrons from the radiation belts by pitch-angle scattering (e.g., Kennel and Petschek, 1966; Lyons et al., 1972). It is also known from recent SAMPEX satellite data that the strongest precipitation occurs during the recovery phase of magnetic storms when the radiation belt electron flux is increasing most rapidly. Some of the loss occurs in microbursts (Blake et al., 1996) or in precipitation bands (Nakamura et al., 1995). This implies that the energization mechanisms that replenish the radiation belt electrons during magnetic storms must be even more effective than they appear since they must build up the electron flux in the face of this enhanced loss. However, wave-particle interactions also involve some energy change. If the wave-particle interactions occur within the plasmasphere, the energy change is small but if they occur outside the plasmasphere, where the plasma density is small and thus the phase velocity of the waves may be large, a substantial energy change can occur and thus heat the electrons. Recent data have shown that the phase space density gradient of the more energetic portion of the radiation belt electrons is sometimes negative with respect to radial distance and thus the enhancement of these electrons cannot always be explained by radial transport (Li et al., 1999; Brautigam and Albert, 2000). It has been suggested that wave-particle interactions of electrons with chorus whistler waves outside of the plasmasphere can heat trapped radiation belt electrons (Temerin et al., 1994; Roth et al., 1998; Summers et al., 1998; Horne and Thorne, 1998) and might thus

provide an explanation for the creation of the higher energy portion of the radiation belt electrons.

2.6. Discussions

Particle distributions often have features that give clues as to the acceleration mechanism that produce them. Thus, Li et al. [1993] were able to infer the mechanism that produced the March 24, 1991 electron belt from the details of the drift echo (Figure 2). Since during magnetic storms the electron fluxes can increase fairly rapidly, one would think that the processes that produce the increase would imprint themselves as specific features in the electron distribution. For a variety of reasons, which may be both physical and instrumental, such detailed features in the electron distribution have usually been difficult to see or difficult to interpret when seen. Perhaps a scarcity of distinctive features in the energy spectra and pitch angle distribution of radiation belt electrons is due to wave-particle interactions, which would tend to diffuse electrons in energy and pitch angle and thus smooth out any distinctive features. In addition many electron radiation belt detectors have been placed on satellites as radiation monitors and lack good energy, pitch angle, or magnetic field resolution. Other detectors, such as the those on the CRRES or the Polar satellites, have had fairly good resolution but pass through the radiation belts too quickly and so are confounded by the spatial-temporal ambiguities that often make analyzing satellite data a challenge. The basic conclusion here is that despite 40 years of radiation belt research, correctly instrumented satellites in the right orbit for studying the electron radiation belts have yet to be flown and the basic acceleration mechanisms are still uncertain.

Acknowledgements

This work was supported by NASA grants (SAMPEX, NAG5-3596, and NAG5-4896) and NSF grants (ATM-9909357 and ATM-9901085). The authors thank numerous colleagues for useful discussions and data. Special thanks are extended to A. Vampola and D. Larson for providing CRRES/MEA and Wind/3D data and M. Looper for providing Figure 3, and also to SAMPEX and Polar/CEPPAD team members.

References

Baker, D. N., J. B. Blake, L. B. Callis, J. R. Cummings, D. Hovestadt, S. Kanekal, B. Blecker, R. A. Mewaldt, and R. D. Zwickl, Relativistic electron acceleration and decay time scales in the inner and outer radiation belts: SAMPEX, *Geophys. Res. Lett.* , *21*, 409, 1994.

Baker, D. N., et al., A Strong CME-related magnetic cloud interaction with the Earth's magnetosphere: ISTP observation of rapid relativistic electron acceleration on May 15, 1997, *Geophys. Res. Lett.* , *25*, 2975, 1998.

Blake J. B., W. A. Kolasinski, R. W. Fillius, and E. G. Mullen, Injection of electrons and protons with energies of tens of MeV into L<3 on March 24, 1991, *Geophys. Res. Lett.* , *19*, 821, 1992.

Blake, J. B., M. D. Looper, D. N. Baker, R. Nakamura, B. Klecker, and D. Hovestadt, New high temporal and spatial resolution measurements by SAMPEX of the precipitation of relativistic electrons, Advances in Space Research, *18*, No. 8, page 171-186, 1996.

Brautigam, D. H., and J. M. Albert, Radial diffusion analysis of outer radiation belt electrons during the 9 October 1990 magnetic storm, *J. Geophys. Res.* , *105*, 291, 2000.

Carlson ,C.W., et al., FAST observations in the downward auroral current region: Energetic up going electron beams, parallel potential drops, and ion heating, *Geophys. Res. Lett.* , *25*, 2017, 1998.

Elkington, S. R., M. K. Hudson, A. A. Chan, Acceleration of relativistic electrons via drift-resonant interaction with toroidal-mode Pc-5 ULF oscillations, *Geophys. Res. Lett.* , *26*, 3273, 1999.

Horne, R. B., and R. M. Thorne, Potential waves for relativistic electron scattering and stochastic acceleration during magnetic storms, *Geophys. Res. Lett.* , *25*, 3011, 1998.

Hudson, M. K., S. R. Elkington, J. G. Lyon, V. A. Machenko, I. Roth, M. Temerin, J. B. Blake, M. S. Gussenhoven, and J. R. Wygant, Simulation of radiation belt formation during storm sudden commencements, *J. Geophys. Res. , 102*, 14087, 1997.

Kennel, C. and H. Petschek, Limit on stably trapped particle fluxes, *J. Geophys. Res.* , *71*, 1, 1966.

Kim, H.-J., and A. A. Chan, Fully-adiabatic changes in storm-time relativistic electron fluxes, *J. Geophys. Res.* , *102*, 22107, 1997.

Li, X., I. Roth, M. Temerin, J. Wygant, M. K. Hudson, and J. B. Blake, Simulation of the prompt energization and transport of radiation particles during the March 23, 1991 SSC, *Geophys. Res. Lett. 20*, 2423, 1993

Li, X., D. N. Baker, M. Temerin, D. Larson, R. P. Lin, G. D. Reeves, M. D. Looper, S. G. Kanekal, and R. A. Mewaldt, Are energetic electrons in the solar wind the source of the outer radiation belt? *Geophys. Res. Lett.* , *24*, 923, 1997.

Li, X., D. N. Baker, M. Temerin, T. E. Cayton, G. D. Reeves, R. A. Christensen, J. B. Blake, M. D. Looper, R. Nakamura, and S. G. Kanekal, Multi-Satellite Observations of the Outer Zone Electron Variation During the 3-4 November 1993 Magnetic Storm, *J. Geophys. Res. , 102*, 14123, 1997.

Li, X., D. N. Baker, M. Temerin, T. E. Cayton, G. D. Reeves, R. S. Selesnick, J. B. Blake, G. Lu, S. G. Kanekal, H. J. Singer, Rapid Enchancements of Relativistic Electrons Deep in the Magnetosphere During the May 15, 1997 Magnetic Storm, *J. Geophys. Res.* , *104*, 4467, 1999.

Lin, R. P., Wind observations of superthermal electrons in the interplanetary medium, Space Science Reviews, *86*, 61-78,1998

Looper, M. D., J. B. Blake, and R. A. Mewaldt, Continuing SAMPEX Observations of Shock-Injected Ultrarelativistic Electrons *Proceedings of the XXVI ICRC, 6, 456-459, 1999, paper SH 2.1.13*

Lyons, L. R., R. M. Thorne, and C. F. Kennel, Pitch-angle diffusion of radiation belt electrons within the plasmasphere, *J. Geophys. Res.* , *77*, 3455, 1972.

Nakamura, R., D. N. Baker, J. B. Blake, S. Kanekal, B. Klecker, and D. Hovestadt, Relativistic electron precipitation enhancements near the outer edge of the radiation belt, *Geophys. Res. Lett.* , *22*, 1129, 1995.

Northrop, T. G., The adiabatic motion of charged particles. Interscience Publishers, New York, 1963.

Paulikas, G. A., and J. B. Blake, Effects of the solar wind on magnetospheric dynamics: Energetic electrons at the synchronous orbit, *Quantitative Modeling of Magnetospheric Processes, 21*, Geophys. Monograph Series, 1979.

Reeves, G. D. et al., The relativistic electron response at geosynchronous orbit during the January 1997 magnetic storm, *J. Geophys. Res.* , *103*, 17559, 1998.

Roth, I., M. Temerin, M. K. Hudson, G. D. Reeves, J. B. Blake, R. S. Selesnick, Resonant heating of energetic storm-time electrons due to substorm-time excited whistler waves, *SUBSTORMS-4*, 593, Edited by S. Kokubun and Y. Kamide, by Terra Scientific Publishing Company/Kluwer Academic Publishers, 1998.

Rowland, D. and J. R. Wygant, Dependence of the large scale, inner magnetospheric electric field on geomagnetic activity, *J. Geophys. Res.* , *103*, 14959, 1998.

Schulz, M. and L. Lanzerotti, Particle diffusion in the radiation belts, Springer, New York, 1974.

Selesnick, R. S., J. B. Blake, W. A. Kolasinski, T. A. Fritz, A quiescent state of 3 to 8 MeV radiation belt electrons, *Geophys. Res. Lett.* , *24*, 1343, 1997.

Selesnick, R. S., J. B. Blake, Dynamics of the outer radiation belt, *Geophys. Res. Lett.* , *24*, 1347, 1997.

Sheldon, R. B., H. E. Spence, J. D. Sullivan, T. A. Fritz, and Jiasheng Chen, The discovery of trapped energetic electrons in the outer cusp, *Geophys. Res. Lett.* , *25*, 1825, 1998.

Summers, D., R. M. Thorne, and F. Xiao, Relativistic theory of wave-particle resonant diffusion with application to electron acceleration in the Magnetosphere, *J. Geophys. Res.* , *103*, 20487, 1998.

Temerin, M., I. Roth, M. K. Hudson, J. R. Wygant, New paradigm for the transport and energization of radiation belt particles, *AGU, Eos*, Nov. 1, 1994, page 538.

Vampola, A. L., J. V. Osborn, and B. M. Johson, The CRRES Magnetic Electron Spectrometer AFGL 701-5A (MEA) *J. of Spacecraft and Rockets, 29*, 1992.

Vampola A. K. and A. Korth, Electron drift echoes in the inner magnetosphere, *Geophys. Res. Lett.* , *19*, 625, 1992.

Vette, J. I., The AE-8 Trapped Electron Model Environment, NSSDC/WDC-A-R&S *91-24*, NASA/GSFC, Greenbelt, Maryland, November, 1991.

3. Figure Captions

Figure 1: CRRES/MEA electron differential fluxes (#/cm^2-s-sr-keV), sorted by L-value (in bins of 0.1 L), and geomagnetic indices for the CRRES period are plotted vs time (in orbit number, the orbital period:$\sim$10 hours).
Figure 2: (Fig. 1 of [Li et al., 1993a]) (a) Data from the CRRES satellite at the time of the March 24, 1991 SSC. Top panel shows count rates as a function of time from four energetic electron channels measuring integral counts above a threshold energy indicated, and also between 10-50 MeV. Middle and bottom panels show the measured electric field E_y in a co-rotational frame and the B_z magnetic field component with a model magnetic field subtracted, in GSE coordinates over the same time interval. (b) Simulated results in the same format as (a) measured at a spatial location corresponding to the trajectory of the CRRES satellite.
Figure 3: Color-coded countrate of 10-20 MeV electrons measured by SAMPEX since its launch on 3 July 1992, into a polar orbit with an altitude of about 600 km and inclination of 82°. The averaging period varies from 1-3 months to remove instrument and spacecraft pointing-mode artifacts. (Adapted from Fig. 1 of M. Looper et al. [1999]).
Figure 4: Various parameters plotted vs. time for the first half of 1995. The panels are (from top): differential flux of electrons (#/cm^2-s-sr-MeV) in the solar wind (every 15 minutes); solar wind velocity (every 12 minutes), V_{sw}; solar wind velocity fluctuation directly calculated from the V_{sw} and then with a 10 hour averaging window; daily averages of the integral flux of electrons (electron/cm^2-s-sr) measured by SAMPEX for $>$0.4 MeV at L=10; and for (2-6 MeV) at L=6.6; daily averages of the differential flux (electron/cm^2-s-sr-MeV) of electrons measured by the LANL sensor onboard geosynchronous satellite (1989-046); D_{st} index.