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The global response of relativistic radiation belt electrons to the January 1997 magnetic cloud

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Abstract. In January 1997 a large fleet of NASA and US military satellites provided the most complete observations to date of the changes in >2 MeV electrons during a geomagnetic storm. Observations at geosynchronous orbit revealed a somewhat unusual two-peaked enhancement in relativistic electron fluxes [*Reeves et al.,* 1998]. In the heart of the radiation belts at L≈4, however, there was a single enhancement followed by a gradual decay. Radial profiles from the POLAR and GPS satellites revealed three distinct phases. (1) In the acceleration phase electron fluxes increased simultaneously at L≈4-6. (2) During the passage of the cloud the radiation belts were shifted radially outward and then relaxed earthward. (3) For several days after the passage of the cloud the radial gradient of the fluxes flattened, increasing the fluxes at higher L-shells. These observations provide evidence that the acceleration of relativistic electrons takes place within the radiation belts and is rapid. Both magnetospheric compression and radial diffusion can cause a redistribution of electron fluxes within the magnetosphere that make the event profiles appear quite different when viewed at different L-shells.

Introduction

Relativistic electron events have been been studied since the dawn of the space age yet their origin and the acceleration process that produces them remain poorly understood. The most commonly-applied model for the relativistic electron acceleration process is the so-called "recirculation" model [*Nishida,* 1976]. Although the recirculation model was developed to explain energization in Jupiter's magnetosphere it has also been widely applied to the Earth's magnetosphere and has been the standard model for relativistic electron events. In this model it is thought that substorm injections produce a 'seed population' which can further gain energy through betatron acceleration as they diffuse across magnetic field lines to lower altitudes [e.g. *Baker et al.,* 1997]. In order to account for the observed increases in energy the recirculation model proposes that the electrons undergo betatron acceleration several times by scattering at low altitudes onto magnetic field lines that are again connected to the outer region of the radiation belts thus 'recirculating' the electrons.

Single satellite measurements showed many characteristics that agreed with the predictions of this model. Primary among them was the observations from geosynchronous satellites which showed that the relativistic electron fluxes tended to peak 2-3 days after the passage of the solar wind disturbance and the initial injection of the seed population [e.g. *Paulikas and Blake,* 1979].

A second class of events was discovered more recently. The CRRES satellite observed the creation of a new ultrarelativistic (E>15 MeV) electron radiation belt which was produced in a matter of minutes due to the passage of a magnetic shock through the magnetosphere [*Blake et al.,* 1992; *Li et al.,* 1993; *Hudson et al.,* 1997]. The January 1997 event does not appear to be consistent with either of these proposed acceleration mechanisms.

The January, 1997 Event

In January 1997 a coronal mass ejection (CME) produced a magnetic cloud that impacted the Earth's magnetosphere. The solar wind conditions and the magnetospheric energetic particle response measured by five geosynchronous satellites has been described by *Reeves et al.* [1998]. Strong substorm activity, development of a storm-time ring current, and enhancement of radiation belt electrons were all observed.

The event was first felt in the Earth's magnetosphere at about 0100 UT on January 10 when a shock leading the coronal mass ejection hit the magnetosphere. Following the shock the interplanetary magnetic field (IMF) slowly rotated from strongly southward to strongly northward (approximately ±20 nT) over a period of about one day, changing sign around 1800 UT on January 10. In addition the coronal mass ejection contained a region of high plasma density which compressed the magnetosphere and increased the magnetic field strength in the radiation belts. The compression lasted from about 1200 UT on January 10 to about 1200 UT on January 11 and peaked at about 0200 UT on January 11.

The relativistic electron enhancement began shortly before 1200 UT on January 10, before the beginning of the magnetospheric compression, and while the energy input into the magnetosphere was still quite strong. Figure 1 shows the temporal flux profiles of relativistic electrons, with energies greater than approximately 2 MeV, from January 8 to 18. Panel A shows data from five geosynchronous satellites from the study by *Reeves et al.* [1998]. In that paper we noted the two-peaked response of the geosynchronous relativistic electron fluxes. The first peak occurred between 1200 UT on January 10 and 1200 UT on January 11 in close correspondence to the times when the high-density solar wind had compressed the magnetosphere. The second peak is a broad peak with maximum fluxes observed on January 15. This second peak has the same general characteristics as the events reported by *Paulikas and Blake* and others.

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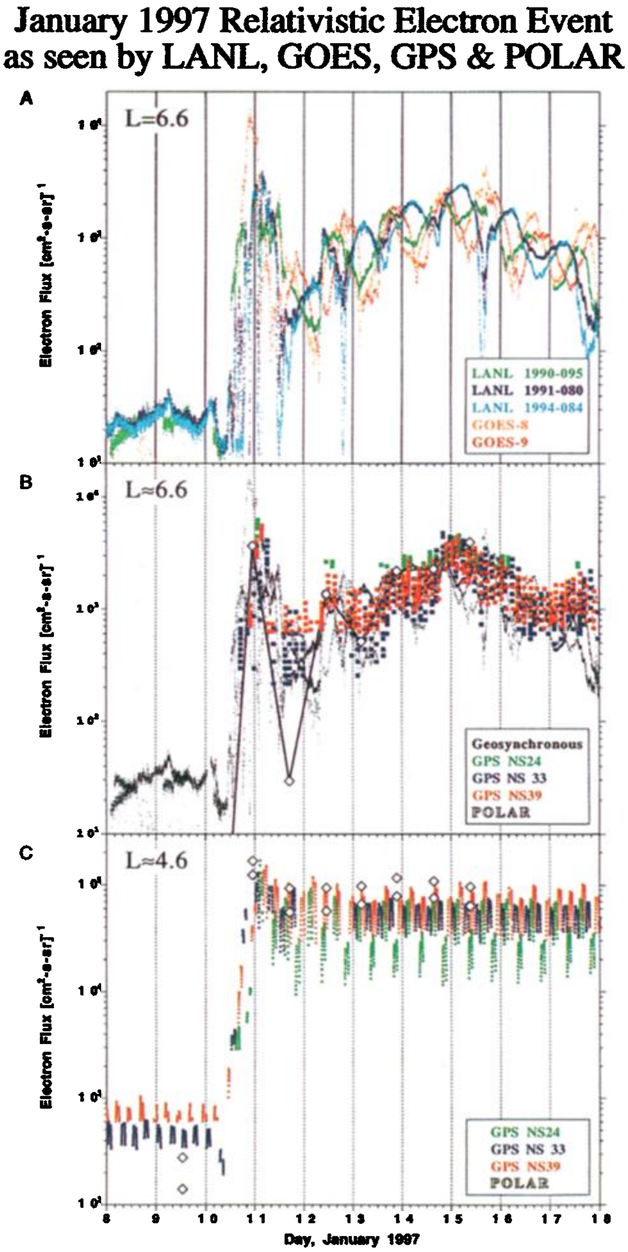

Figure 1. Temporal profiles of relativistic electron fluxes. Profiles are shown for geosynchronous orbit (top panel), at L≈6.6 overlaid on the geosynchronous data (middle panel), and at L≈4.6 near the peak of the electron belts (bottom panel). The energies plotted are integral channels with thresholds 1.6 MeV for GPS, 1.74 MeV for POLAR, 1.8 MeV for LANL, and 2 MeV for GOES.

To further investigate the origin and acceleration of relativistic electrons we examined data from six additional satellites that were simultaneously measuring the fluxes of >2 MeV electrons during this event. Those satellites were POLAR, SAMPEX, HEO, and the GPS Navstar-24, -33, and -39 satellites. The lower two panels, B and C, in Figure 1 show data from the three GPS satellites and from POLAR for two different L-shells. (SAMPEX and HEO had similar profiles but are not shown for simplicity.).

Fluxes measured off the magnetic equator but at the same L are assumed to be roughly equal. Figure 1-B shows that this is the case here. The GPS satellites are in a 12 hour, 4.1 R_E, circular orbit which takes them through the peak of the radiation belts at a point near the magnetic equator. POLAR is in an 18 hour, 2×9 R_E, elliptical orbit with perigee nearly above the north pole. Although POLAR and GPS cross L≈6.6 at relatively high magnetic latitudes the fluxes have nearly the same temporal profile as seen at geosynchronous orbit, near the magnetic equator. This match gives us confidence to combine data from different L-shells, measured by different satellites into a single coherent picture.

Figure 1-C again shows data from POLAR and the three GPS satellites but now for L≈4.6 which lies near the expected peak of the radiation belts. It is apparent that the flux profiles at L≈4.6 are distinctly different that the profiles at L≈6.6. Although there is some evidence of a peak at L≈4.6 between

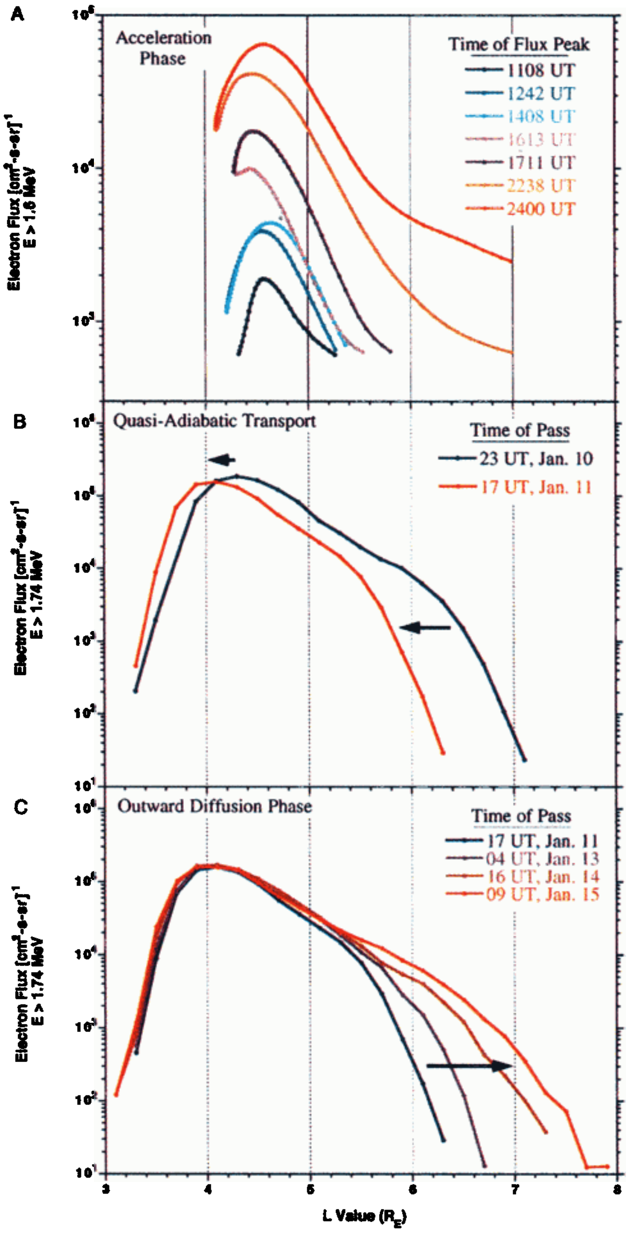

Figure 2. Radial profiles of relativistic electron fluxes. Top panel: GPS fluxes from 1108 to 2400 UT on January 10 show that acceleration occurs throughout the radiation belts (L=4-7) in approximately 12 hours. Middle panel: Two POLAR passes show a shift of the radiation belt profiles as the magnetic field decreases following the passage of the high-density solar wind. Bottom panel: Four subsequent POLAR passes show the fluxes increasing outside L=5.5 while they remain relatively stable inside L=5.5.

1200 UT, January 10 and 1200 UT, January 11 it is much less pronounced than at L≈6.6. In addition the broad, delayed peak which was thought to be a general characteristic of relativistic electron events is conspicuously absent. Rather the fluxes appear to climb up over a period of about 12 hours beginning slightly before 1200 UT, January 10 and then decay slowly. (Longer-term plots show the fluxes at L≈4.6 decreased slowly until about January 27 when another event began.)

Radial Profiles of the Relativistic Electron Belts

Acceleration Phase

Further insight into the structure and dynamics of the relativistic electron belts can be gained by examining the radial profiles in Figure 2. Panel A shows the initial acceleration period on January 10. Here we have plotted relativistic electron flux from GPS satellites NS-33 and NS-39 as a function of the magnetic L value. The times noted in the figure are the times (after 0 UT on January 10) that the GPS satellites passed through the peak in the electron belt. Between 1200 UT and 2400 UT the fluxes at the peak of the electron belts increased by more than a factor of 30. Along with Figure 1 this shows that the acceleration occurred within 12 hours at all L between L≈4-7.

The 4.1 R_E circular orbit of the GPS satellites brings them through the flux maximum as they move toward the equator and then back through the flux maximum as they move away from the equator. Notice that the fluxes increased even between the inbound and outbound passes in a single orbit (e.g. 1613 to 1711 UT). Because the fluxes increased with each pass of the satellite through the peak of the radiation belts we can conclude that the acceleration was somewhat smooth and continuous.

Thus the acceleration of 2 MeV electrons in this event was faster than the 2-3 days expected in the recirculation model but considerably slower and more continuous than the acceleration produced by shock-driven events such as the March 1991 CRRES event. *Li et al.* [1998] have argued that a small interplanetary shock in the January 1997 event may have accelerated electrons at L≈4 up to energies of approximately 800 keV but this still requires a different acceleration mechanism to take those electrons from 800 keV to >2 MeV.

Transport Phase

As seen in Figure 1, early on January 11 the fluxes at L≈6.6 decrease by more than an order of magnitude while the fluxes at L≈4.6 decrease by perhaps a factor of 2. The reason for this can be seen in the Figure 2-B which shows two consecutive passes of POLAR. Between 23 UT on January 10 and 17 UT on January 11 it appears as if the entire relativistic electron population has moved radially inward. Since the peak moves inward from L≈4.4 to L≈4.0 there is only a small change in the fluxes at L=4.6 while at L=6.6 the radial gradient is steeper and the flux change is much larger. This kind of collective shift of the radiation belts has not been previously reported. The inward shift is coincident with the de-compression of the magnetosphere associated with the decrease in solar wind plasma density which suggests that the particle fluxes are responding to the reconfiguration of the magnetic field.

We can assume that if decompression of the magnetosphere causes an inward radial shift of the radiation belts then the original compression of the magnetosphere must have caused an outward radial shift. This cannot be directly confirmed however because any radial transport during the compression of the magnetosphere is superimposed on the acceleration phase.

Diffusion Phase

The remaining puzzle is the cause of the broad, delayed maximum at L≈6.6 which was thought to be characteristic of the acceleration process. Figure 2-C again shows the profiles from POLAR for four passes leading up to January 15. During this period the peak of the radiation belt remains fixed at L≈4.0 but the flux profiles broaden. Particularly at the outer edge of the radiation belts (L=5.5-8.0) the radial gradients become significantly less steep resulting in a gradual, but large, increase in the fluxes there. This signature is characteristic of slow diffusion outward from the more stable peak toward the outer regions of the magnetosphere where the particles can be lost to the solar wind.

While the radial profiles at fixed energy are consistent with outward radial diffusion they do not constitute proof. However, further evidence has been provided by *Selesnick et al.* [1998]. They examined the same POLAR passes shown here both at fixed energy and at fixed phase space density. Their results confirm that a peak in phase space density was produced at L≈4–5 and that the radial gradient at L>5.5 reversed direction as compared to quiet times. Thus, even if inward radial diffusion from the tail continues, the presence of a peak in phase space density inside geosynchronous orbit will also produce outward radial diffusion from that source – which is consistent with our observations. Taken together these two observations suggest not only the existance of outward radial diffusion but also strongly imply that the acceleration mechanism that accelerates electrons to energies greater than several MeV operates in the heart of the radiation belts, perhaps near L≈4.

Summary

By combining observations from a large number of satellites a new picture of the structure and dynamics of relativistic electrons in the Earth's radiation belts emerges. This picture has a number of features which were not seen in previous studies and which cannot be understood in the context of either the recirculation model or the shock-acceleration model. Those features can be summarized as follows:

Acceleration up to energies of a few MeV can occur in 12 hours, four to six times faster than previously thought and too fast to be explained by recirculation. While an interplanetary shock may have accelerated electrons up to energies of 800 keV in a matter of minutes some other process is required to explain the continuous increase in >2 MeV electron fluxes over the next 12 hours. One potential candidate is resonant acceleration in the strong ULF wave fields that are frequently observed in geomagnetic storms [*Baker et al.*, 1998].

The delay between the storm main phase and the peak in relativistic electron fluxes which is characteristic of observations at geosynchronous orbit is not characteristic of the radiation belts as a whole but is confined to the outer regions of the electron belts (L>5.5). We conclude that the delayed flux peak seen at geosynchronous orbit is not caused by a slow acceleration process (such as recirculation) operating over several days. Rather it is probably caused by diffusive transport of particles outward from the more stable peak of the radiation belts. This outward diffusion is opposite to the direction during magnetically quiet times. The production of a peak in phase space density at L≈4-5 and the apparent outward radial diffusion from that peak are strong evidence that the acceleration of electrons to relativistic energies occurs in the heart of the radiation belts probably through a localy operating process.

During magnetospheric compressions and decompressions, the entire radiation belts can shift radially on time scales of hours. The outward and inward shifts are probably caused by the compression and de-compression of the magnetosphere associated with changes in solar wind dynamic pressure. Large magnetospheric compressions do not occur in all storms though and therefore most events are not expected to produce a double-peaked response in the outer radiation belts.

The apparent shift observed in the January 1997 event is also notable because it is opposite to that expected if all three adiabatic invariants are conserved. Conservation of the third adiabatic invarient implies that magnetic de-compression should move particles outward to conserve the total magnetic flux in a drift orbit while we observe the opposite. The radial shifts seen in the January 1997 storm are, however, consistent with conservation of the first two invariants and it is reasonable to expect the third invarient was not conserved in this event because of the large and rapid changes in the geomagnetic field.

Although these observations answer several long-standing questions in magnetospheric physics they leave unanswered two important questions for further study: First, what is the physical mechanism that is responsible for the initial acceleration of the relativistic electrons in the radiation belts? and Second, what solar wind conditions are necessary, or sufficient, to activate that mechanism and produce a relativistic electron event? The resources which are now available as part of the International Solar Terrestrial Physics and Geospace Envrionment Modelling programs will certainly help answer those questions as well.

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