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Relativistic Electron Microbursts

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We report the first satellite observations of relativistic (>1 MeV) electron precipitation in microbursts with measured durations of less than 1 s. Microbursts of lower-energy electrons (10–100 keV) have been found to occur preferentially in the early daylight hours and to be closely associated with VLF chorus emissions. In contrast, the relativistic electron microbursts occurred more frequently near 2230 LT than 1030 LT, and no association was found with ELF/VLF chorus, consistent with the fact that resonant interactions with ~1-MeV electrons require significantly lower frequencies. The available data on these relativistic microbursts thus appear to indicate that many of the bursts may be due to wave-particle interaction not with whistler mode chorus but possibly with other waveforms. The locations of many of the relativistic microbursts are concentrated at the outer edge of the trapped radiation belt, where the gyroradii of the electrons are comparable to the curvature of the magnetic field lines and stable trapping may therefore not occur. The preferred location of the microbursts, which may be primarily spatial in character, implies the possible importance of irregularities in the magnetic field lines near the trapping boundary as the responsible mechanism.

INTRODUCTION

Relativistic electrons are known to be present in the radiation belts with pronounced spatial and temporal enhancements and depletions [e.g., *Baker et al.*, 1986], but the source and loss mechanisms are not well understood. Bursts of relativistic electrons precipitating into the atmosphere have been observed for durations typically of 1–10 s [*Imhof et al.*, 1991]. In order to understand the precipitation mechanisms it is important to study these bursts in more detail since the different width bursts may or may not be produced by the same class of mechanism(s) which may be either spatial or temporal in nature.

Microbursts of precipitating electrons were first described by *Anderson and Milton* [1964]. The electrons were detected from balloons by measuring the X rays produced when they encountered the atmosphere, and the electron energies were mostly in the tens to hundreds of keV range. The microbursts were characterized by durations of ~0.2 s and interburst spacings of ~0.6 s. Most observations of microbursts have been conducted from balloons or rocket-borne parachute deployments and have involved measurements of the bremsstrahlung X rays produced by the electrons as they encounter the atmosphere [e.g., *Parks*, 1978; *Rosenberg et al.*, 1981; *Bering et al.*, 1988]. Microburst events have been found to be closely associated with VLF chorus waves observed on the ground, [*Rosenberg et al.*, 1990].

One set of early observations of microbursts was made from the INJUN 3 satellite and involved the direct measurement of precipitating electrons of >40 keV [*Oliven et al.*, 1968]. The microbursts were found to occur preferentially in the early daylight hours and seldom near midnight. Oliven et al. reported that the microbursts occur predominantly at $L =$ 6–8.5 and MLT = 0430–1230. They found that the microbursts were always accompanied by VLF chorus, but one-to-one associations between the microbursts and chorus emissions were not observed. The latter can be attributed to the fact that the electron precipitation induced by chorus in whistler mode gyroresonance interactions observed at one hemisphere would first be deposited at the conjugate hemisphere.

Short bursts of electrons with energies above 45 keV were studied with data from the S81-1 low-altitude polar-orbiting satellite [*Imhof et al.*, 1989]. The bursts met all of the criteria for microbursts and had soft spectra with negligible flux above 1 MeV. The study included 87 satellite passes. Bursts occurred in 44 (72%) out of 61 daytime passes and in 14 (54%) out of 26 nighttime passes, thus indicating a higher occurrence rate during daytime. In all 33 cases when the satellite was near Siple Station and microbursts were detected, chorus activity was also observed at ground stations within nearby times.

Measurements on the S81-1 satellite of electrons at energies above 1 MeV in bursts longer than 1 s were recently published [*Imhof et al.*, 1991]. That study was limited to bursts with observed durations ranging from 1 to 10 s which were found primarily at L values between 4 and 6. These relativistic electron precipitation bursts of >1-s observed duration were found much more often near midnight than noon.

In this paper we present for the first time observations of relativistic electron microbursts with durations typically of <1 s. Previously reported studies of microbursts have involved primarily electrons of energy below a few hundred keV. For relativistic electron energies of >1 MeV and on typical L shells of $4 < L < 7$, gyroresonant interactions with ELF/VLF chorus are not expected to be important, since wave frequencies required for equatorial interactions are typically <100 Hz, whereas the lowest observed ELF chorus frequencies are >500 Hz [*Burtis and Helliwell*, 1976].

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However, we note that the relativistic microbursts reported here are usually accompanied by significant lower-energy (few hundred keV) components which could have been precipitated in equatorial interactions with chorus, with the >1-MeV component being due to interactions along the field line at locations substantially away from the geomagnetic equator. (At $L = 5$ and 1-kHz wave frequency, gyroresonance with 1-MeV electrons would occur at a geomagnetic latitude of 25°.)

Precipitation of relativistic electrons can also result from interactions with other wave modes, as noted by *Thorne and Andreoli* [1980], who found that strong nightside relativistic electron precipitation activity (typically steady, not bursty in nature like the microbursts discussed here) was most closely associated with electrostatic ion cyclotron (EIC) waves. While we recognize that such waves may indeed play a dominant role, we consider here only possible association with chorus, since no data on EIC waves are available as they are not observed on the ground. We also consider the possibility that spatial irregularities in the geomagnetic field lines are responsible.

DESCRIPTION OF INSTRUMENTATION

The Stimulated Emission of Energetic Particles (SEEP) experiment on the S81-1 spacecraft contained an array of cooled silicon solid-state detectors to measure electrons and ions [*Voss et al.*, 1982]. The data were acquired over the period from May 28, 1982, to December 5, 1982. The S81-1 three-axis stabilized satellite was in a Sun-synchronous 1030 and 2230 LT polar orbit (inclination 96.3°) at altitudes from 170 to 280 km. The data used in this study were obtained primarily from two electron spectrometers, one at a zenith angle of 0° (ME 1) and the other at a zenith angle of 180° (ME 2). Both detectors had acceptance angles of ±30°, and at these altitudes the fields of view at high geomagnetic latitudes were entirely within the bounce loss cone. The ME 1 detector responded to electrons about to precipitate into the atmosphere, whereas the ME 2 sensor responded to the backscattered electrons. Except for the entrance aperture the silicon detectors in both spectrometers were surrounded by plastic scintillator anticoincidence shields for background reduction. For electrons the threshold energy for detection by the anticoincidence counters was ~1 MeV due to a combination of the shielding from the silicon detector and the signal threshold. The geometric factor was 3.09 cm^2 sr with an acceptance angle of ±30°. The bulk of the data presented here was acquired by the ME 1 anticoincidence detector with the ME 2 anticoincidence counter providing a measure of background response. Some lower-energy electron data presented make use of the silicon detector in the ME 1 spectrometer. Fluxes of electrons above 45, 100, and 300 keV were obtained from the outputs of scalers which, as with the anticoincidence counters, recorded counts during successive 0.064-s intervals. The silicon detectors were 1000 μm thick and had geometric factors of 2.47 cm^2 sr.

Some data are presented here from the P78-1 satellite, which was launched on February 24, 1979, into a Sun-synchronous, noon-midnight near-circular polar orbit at ~600 km altitude. The section of the satellite containing the electron spectrometer used here spun about an axis perpendicular to the orbit plane with a period of about 5.5 s. The silicon electron sensor was surrounded by a plastic scintillator anticoincidence shield for background reduction. The counts recorded in the anticoincidence counter provided a measure of the electron flux with a threshold energy of 1 MeV, a geometric factor of 0.77 cm^2 sr, and an acceptance angle of ±15°.

The wave data used in this study were acquired with the Stanford University broadband ELF/VLF receivers located at Siple and Palmer stations, Antarctica, and Roberval, Quebec (geomagnetic conjugate to Siple Station). These receivers were operated nearly continuously during 1982 in a synoptic mode (recording 1 out of every 5 min) and also continuously during overpasses of the SEEP satellite within ±30° longitude of the stations and/or their conjugate region. The recordings were generally made in analog form on reel-to-reel $\frac{1}{4}$-inch audiotapes. The data were high-pass filtered with a lower cutoff frequency of 300 Hz. The linear dynamic range of the preamplifier and line receiver systems was ~120 dB.

PRESENTATION OF THE MEASUREMENTS

In Figures 1–3 the precipitating electron fluxes above 1 MeV, 300 keV, 100 keV, and 45 keV are plotted as a function of time for three nighttime passes of the S81-1 satellite in which bursts were observed for short time durations. The data are plotted with the time resolution of 0.064 s in which the data were originally acquired. For an event to qualify as a burst, it was required that the counting rate in the ME 1 spectrometer, which was viewing upward, reach a value for at least two 0.064-s intervals greater than 120 counts/s, which is equivalent to a flux above 38.8 el/cm^2 sr s. The ME 1 value must be statistically significant above that in the ME 2 detector which had an identical acceptance angle in the downward direction. The events were manually selected with the aforementioned criteria. Microbursts are taken to be those bursts in which the full width at one-fifth the maximum net flux above the background before and after the burst is >0.064 s and <1 s, and relativistic microbursts are taken to be those that display these features in the integral counting rates above 1 MeV. The criterion of a full width at one-fifth maximum flux was arbitrarily selected to provide a convenient and reliable test that could be applied to the data. From the plots of flux versus time it is clear that there is a continuum of events that would qualify as microbursts to varying degrees of conformance. The microbursts selected are dependent upon the details of the acceptance criteria, but analyses indicate that the conclusions drawn from the data are not significantly dependent upon the selection criteria.

Examples of relativistic microbursts that are the subject of this paper are indicated by arrows in Figures 1–3. The arrows are located at the times of maximum counting rate in each microburst. All of the indicated microbursts were obtained using the selection criteria discussed above. An example of data from a daytime pass with microbursts is provided in Figure 4. The data in Figures 1–4 were acquired with the ME 1 electron spectrometer at 0° zenith angle, and the fluxes given are based on raw counting rates with no background subtraction. Many of the bursts of less than 1 s duration observed with this spectrometer are isolated, but some occur in trains of several narrow bursts. More than one train is observed on certain satellite passes. Both the temporal structure and occurrence features of these bursts are

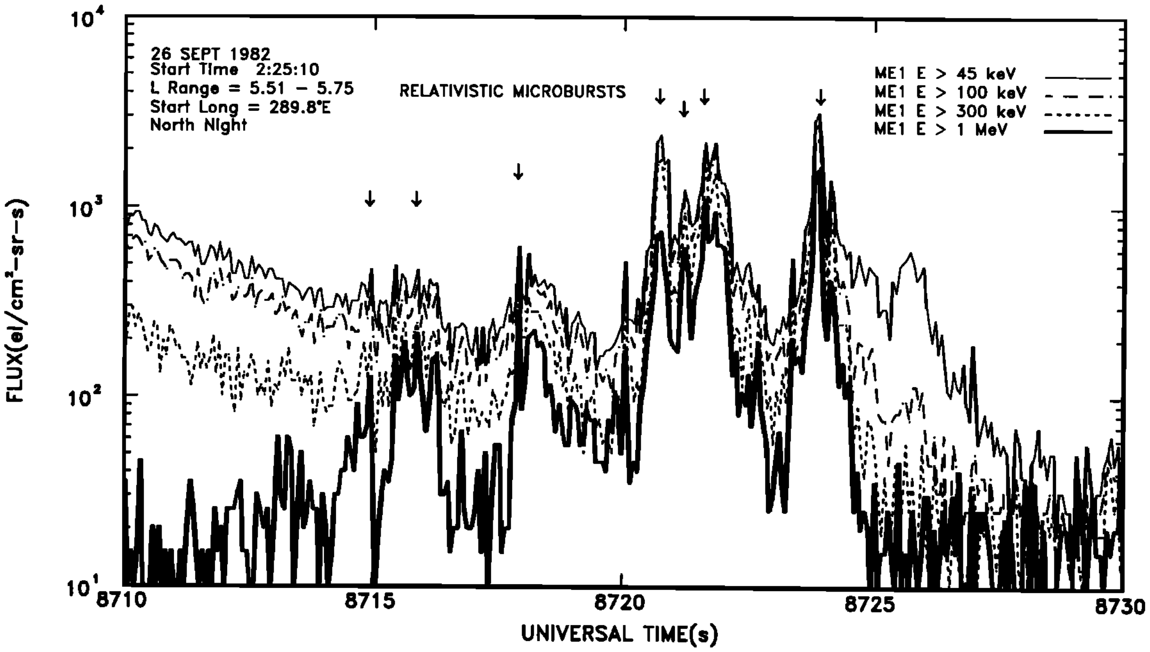

Fig. 1. The fluxes of precipitating electrons above various energies versus time for a pass of the S81-1 satellite in the nighttime.

identical to those of previously reported microbursts. Accordingly, we refer to these short pulses as microbursts in the rest of the paper. The microbursts of >1-MeV electrons are generally less significant than the previously studied wider (>1 s) bursts in terms of energy loss rates, and in most past analyses, only bursts longer than 1 s were included. As in the examples shown, the relativistic microbursts display a variety of electron energy spectra with the fluxes sometimes being predominantly above 1 MeV. For example, on September 26, 1982, at 8720–8725 s (Figure 1) the >1-MeV fluxes were nearly the same as the >45-keV fluxes. At other times, such as the case of September 28, 1982, around 6280 s (Figure 2), the >45-keV flux is much greater than that for >1 MeV.

The distributions in L shell of the peak flux of each microburst of precipitating relativistic electrons observed from the S81-1 satellite are plotted in the top panel of Figure 5. Most of the microbursts occurred in the interval L = 4–6 with a median value near L = 5, similar to those of the previously reported 1- to 10-s duration bursts [*Imhof et al.*, 1991], which are repeated in the bottom panel of Figure 5 for geomagnetic conditions comparable to those existing when the microbursts were observed.

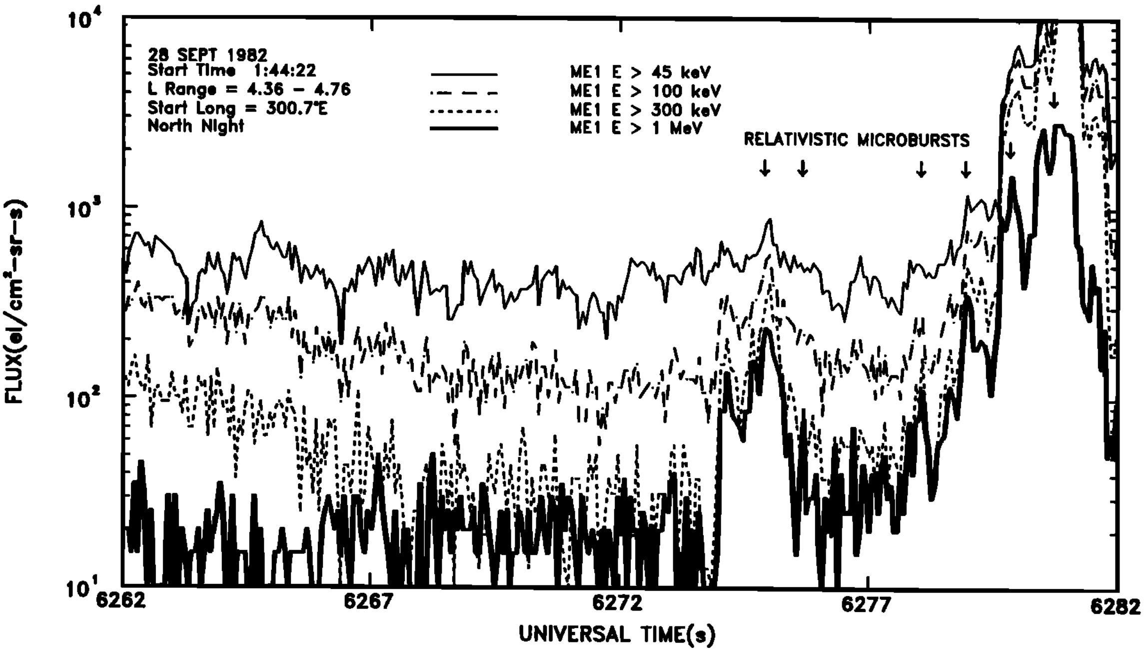

Fig. 2. Same as Figure 1 for a second pass.

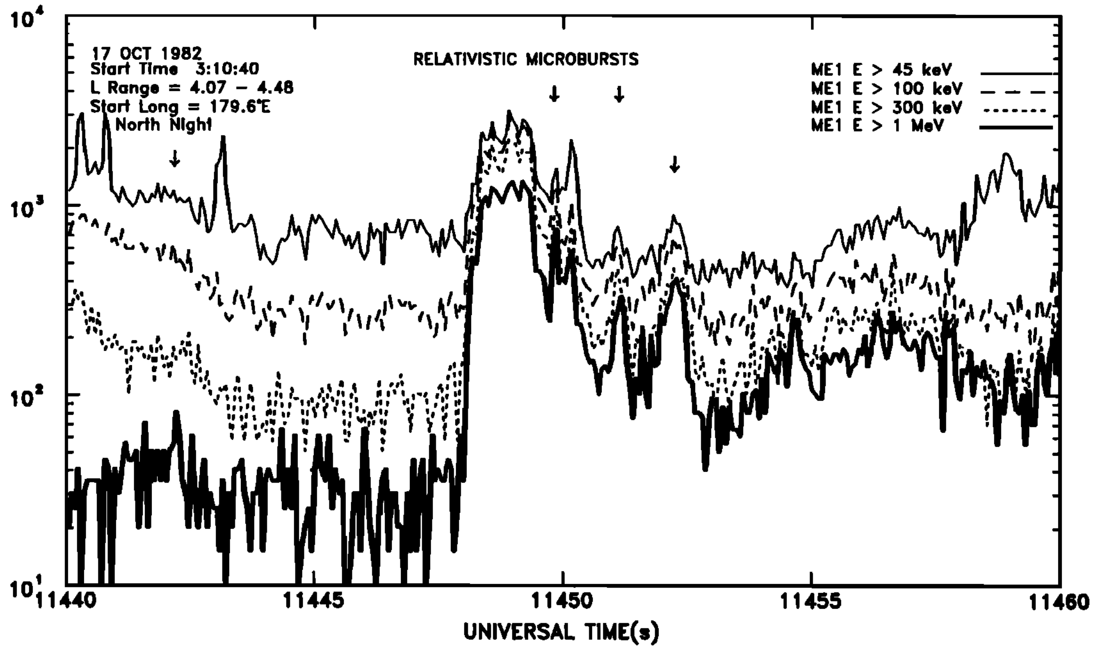

Fig. 3. Same as Figure 1 for a third pass.

From electron >1-MeV flux measurements on the spinning (5.5-s period) P78-1 satellite it was possible to obtain the *L* shell location of both the trapping boundary and any bursts on the same satellite pass. One-to-one comparisons between the locations of these quantities could be made with that set of data, although the sensitivity provided for studying microbursts was less than that provided in the SEEP data used here. A comparison of the bursts and the trapping boundary, provided in Figure 6, indicates that many of the bursts of >1 s duration occurred near the positions of the trapping boundary at the time that each burst was observed. From Figure 5 we conclude that many of the relativistic microbursts also occur near the trapping boundary.

Microbursts were observed from the S81-1 satellite on 42 of 90 nighttime passes (47%) and on only 9 out of 64 daytime passes (14%). Thus the relativistic electron microbursts occurred much more often near 2230 LT than near 1030 LT. This local time preference of relativistic microbursts is opposite to the published local time occurrence of chorus bursts [*Burtis and Helliwell*, 1976] and of the lower-energy electron microbursts [*Oliven et al.*, 1968; *Imhof et al.*, 1989]. We note that microbursts with much softer energy spectra were observed

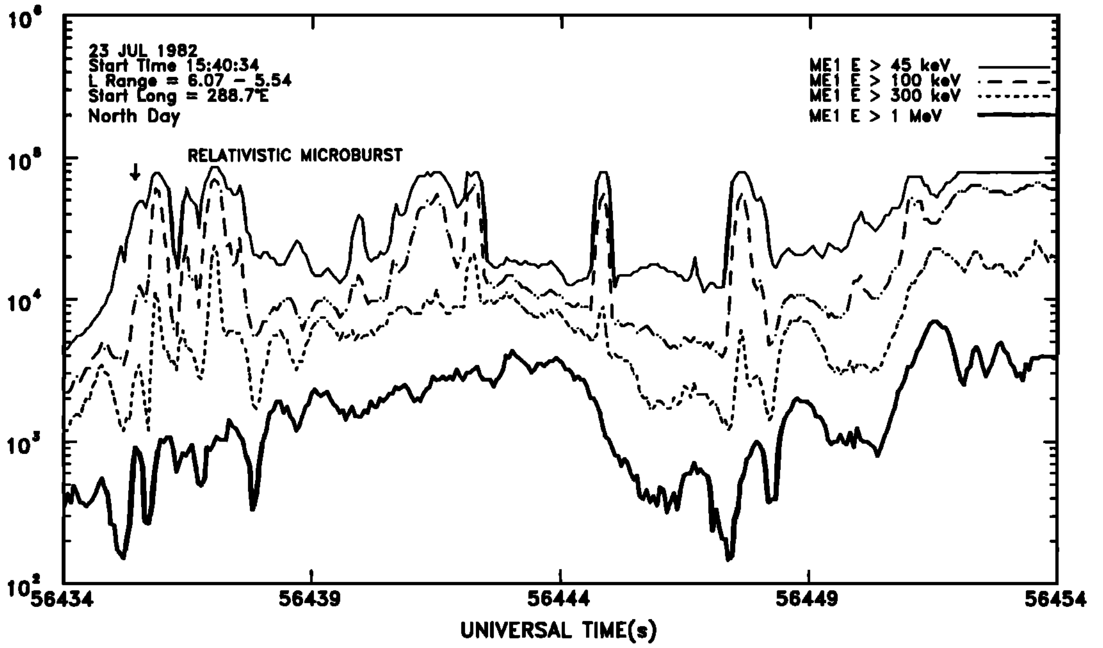

Fig. 4. The fluxes of precipitating electrons above various energies versus time for a pass of the S81-1 satellite in the daytime.

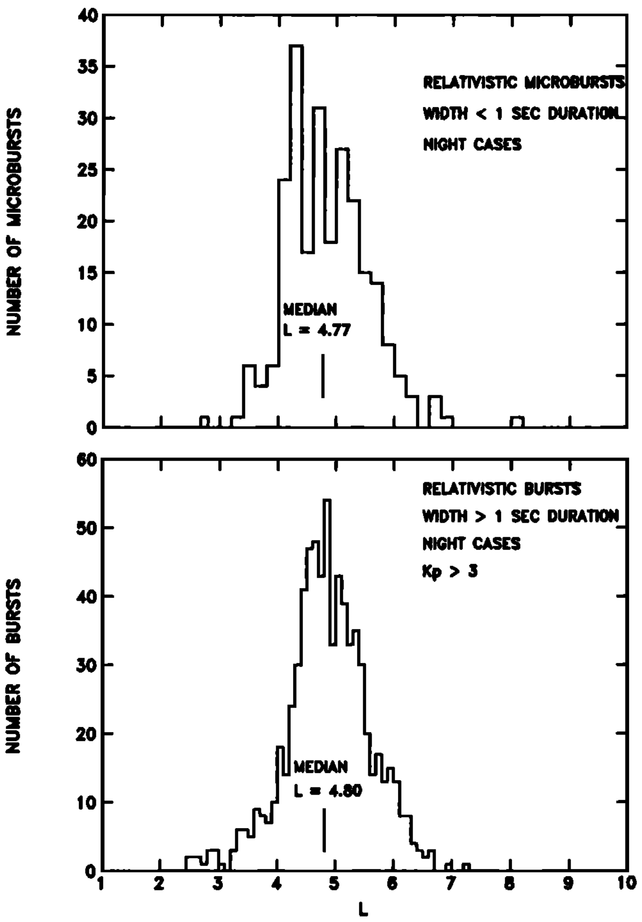

Fig. 5. (Top) The number of microbursts of precipitating relativistic electrons at nighttime versus L shell. (Bottom) The number of bursts 1–10 s wide versus L shell for $Kp > 3$.

from the same satellite. An example of such soft microbursts observed in the daytime is shown in Figure 7.

The question as to whether or not the microbursts are associated with the level of geomagnetic activity is addressed in Figure 8. Here the distributions of values of Kp, AE, and Dst are plotted both for times when microbursts were observed and for the entire several-month time period. One concludes that microbursts occurred preferentially when the Kp and the AE indices were higher than normal.

The possible association of precipitating >1-MeV electrons with whistler mode chorus was investigated by examining simultaneous ELF/VLF wave data taken at times of satellite passes close to Siple Station, Antarctica, or its conjugate point at Roberval, Quebec. There were 26 nighttime passes with relativistic microbursts in the longitude range 250°–310°E in which simultaneous wave data were recorded at Siple or Roberval. Chorus was observed in only five of these cases (19%). Figure 9 shows an example of the simultaneous wave and particle data. In view of the relativistic energies of the electrons and the possibilities of cyclotron resonance interactions with waves at low frequencies, wave data in the 0.3- to 5-kHz range are shown. In the satellite pass shown, relativistic electron microbursts were observed, and chorus features were evident in the waves recorded on the ground, but one-to-one correlations were not observed. Daytime data were recorded at 250°–310°E on eight passes when wave data were recorded at Siple. ELF/VLF chorus events were observed in one of these cases, whereas neither chorus nor any other discrete ELF/VLF waves were observed for the remaining seven passes. The locations of the relativistic microbursts with or without the presence of magnetospheric wave activity are plotted in Figure 10. Clearly, there is no obvious longitudinal correlation between the presence of microbursts alone and those which were accompanied by ELF/VLF chorus activity, indicating that the lack of correlation between relativistic electron microbursts and whistler mode chorus wave activity is not likely to be due to the geometry of the measurements. Thus we conclude that chorus events are generally not associated with relativistic electron microbursts. The frequency of occurrence of electron microbursts at two local times and with and without the presence of chorus bursts or other wave activity is summarized in Table 1 and Figure 11.

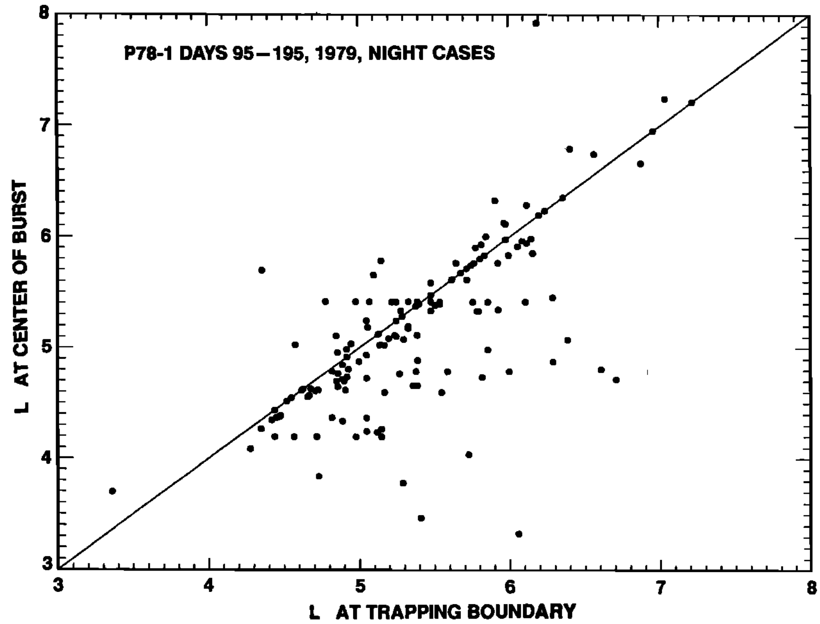

Fig. 6. The L shell location of electron precipitation bursts of >1 s observed duration versus the L shell location of the trapping boundary measured on the same pass of the P78-1 satellite.

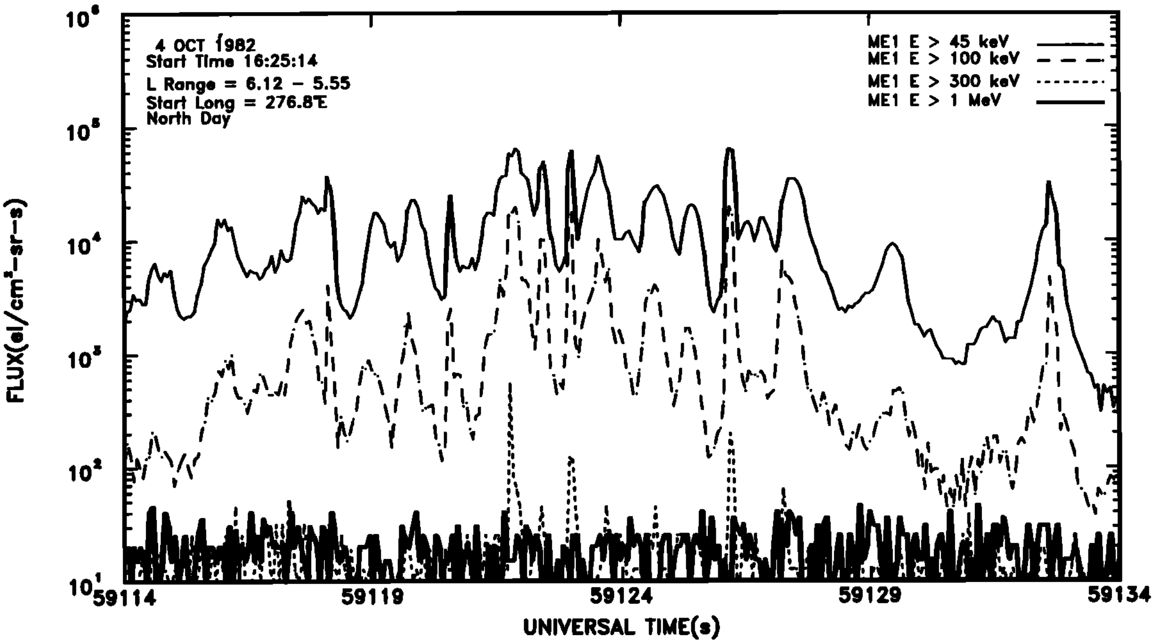

Fig. 7. The fluxes of precipitating electrons above various energies versus time for a pass of the S81-1 satellite in the daytime.

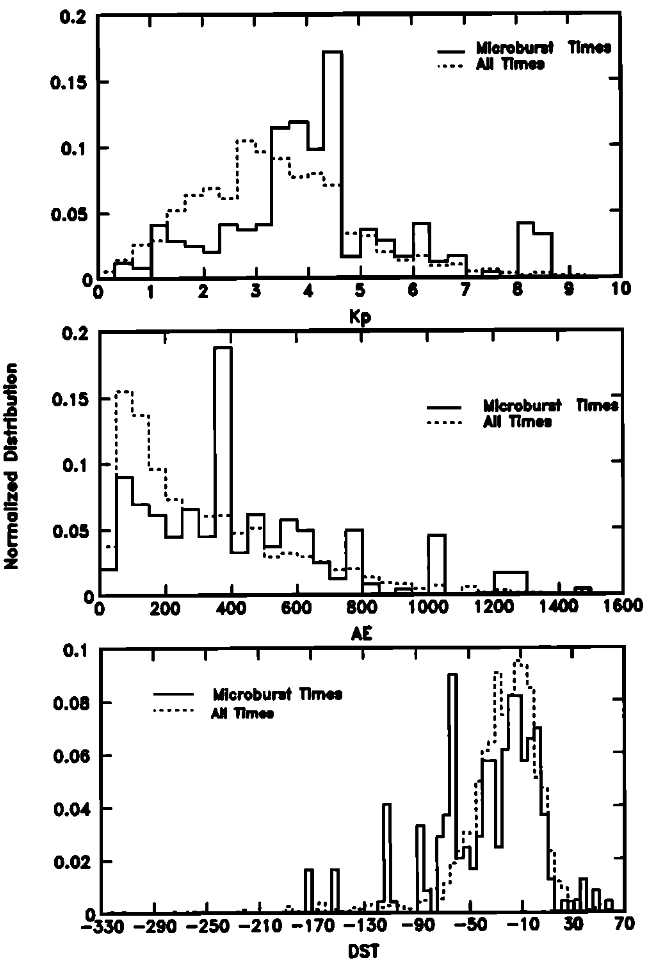

Fig. 8. The distributions of *Kp*, *AE*, and *Dst* for times of microburst observations compared to average distributions.

DISCUSSION

For relativistic electron precipitation, similar locations were found for the occurrences of both wide bursts and narrow microbursts, leading to speculation as to whether they might originate from the same precipitation mechanism. When considering the responsible loss mechanism(s), it is important to recognize that sometimes several microbursts occur within a single wide burst. Such bursts might be considered as trains of microbursts.

Some relativistic electron precipitation bursts, many of which were observed in the drift loss cone, were previously found to occur in the vicinity of the plasmapause position based on the *Kp* index [*Imhof et al.*, 1986]. The bursts were predominantly in the *L* shell range of ~4 to ~6 and therefore probably near the trapping boundary. Many of the relativistic electron precipitation spikes reported here have been found to occur very close to the outer boundary of the radiation belt measured on the same satellite pass. Enhanced precipitation is known to occur often near the "last closed field line." From a low-altitude polar-orbiting satellite the precipitation at this location often displays *L*-dependent energy selectivity on a time scale of a few seconds or a distance of a few kilometers [e.g., *Imhof*, 1988; *Imhof et al.*, 1991]. The precipitation mechanism may be due to the loss of adiabatic motion when the radius of field line curvature is less than an order of magnitude greater than the gyroradius of the electrons. For various magnetic field models, theoretical calculations have been made of the expectations [*Popielawska et al.*, 1985; *Buchner and Zelenyi*, 1989; *Popielawska and Zwolakowska*, 1991].

Contrary to the expectations of temporal characteristics for the relativistic electron microbursts they may be entirely spatial in nature, and if so, the thickness would be of the order of 8 km or less, a width comparable to that of some auroral arcs. The occurrence of multiple bursts on the same

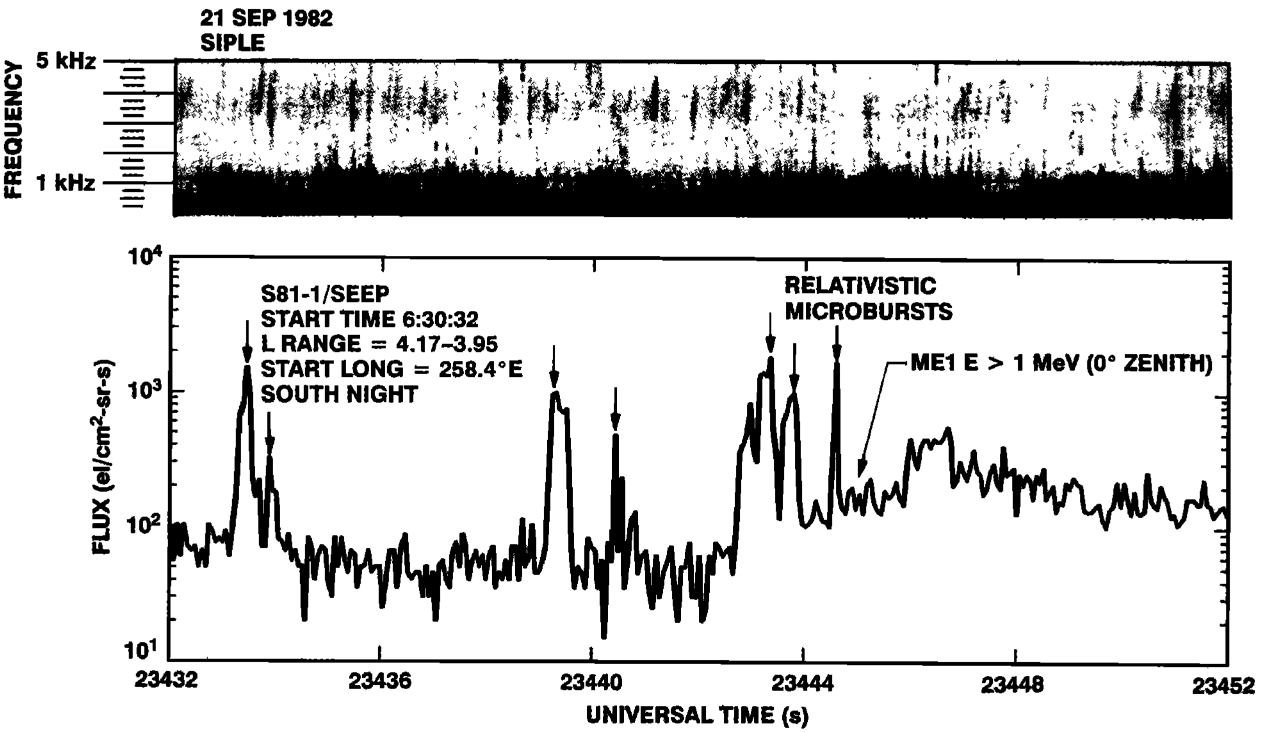

Fig. 9. Simultaneous wave intensities and electron fluxes versus time for a pass of the S81-1 satellite in the nighttime.

satellite pass might be accounted for in such a model in terms of fine-scale variations in the magnetic field configuration. Another example of analogous precipitation patterns that are spatial in nature has been reported [*Vondrak et al.*, 1983]. In that study, detached arcs of ionization having comparable spacings to some of those presented here were observed with the Chatanika incoherent scatter radar and found to have widths and spacings that were steady for about 40 min.

Soft microbursts are usually associated with chorus wave activity [*Oliven et al.*, 1968; *Imhof et al.*, 1989; *Rosenberg et al.*, 1990], whereas the relativistic microbursts presented here were generally not accompanied by any wave activity observable on the ground. We note here that, as mentioned above, chorus waves at typical observed frequencies (>500 Hz) are not expected to interact in cyclotron resonance with >1-MeV electrons at the geomagnetic equator; however, our result indicates that possible interactions at locations off the equator also do not play an important role. Since no data were available on other wave modes (in particular EIC waves previously suggested as possible drivers for relativis-

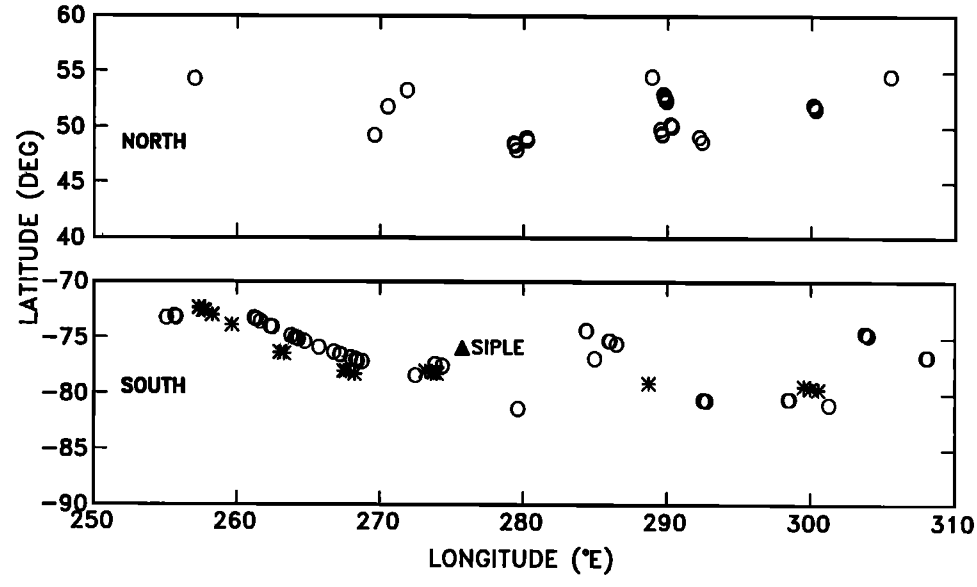

Fig. 10. The locations of microbursts observed in the 250°–310°E longitude interval. Relativistic microbursts which are of <1-s duration appear with simultaneous wave data. There are 106 microbursts on 26 satellite passes and 29 satellite passes with no microbursts. Asterisks denote chorus at Siple, and open circles indicate no chorus at Siple.

TABLE 1. Electron and Wave Data Summary for >1-MeV Electrons

Item	1030 LT	2230 LT
Number of passes (250°–310°E)	64	90
Number of passes with microbursts	9	42
Fraction of passes with microbursts	0.14	0.47
Average number of microbursts per pass	0.67	1.73
Number of passes with microbursts and with waves recorded at Siple	8	26
Number of passes having microbursts in which chorus was recorded	1	5
Fraction of passes having microbursts in which chorus was recorded	0.125	0.192
Fraction of all passes having both microbursts and chorus	0.018	0.090

tic electron precipitation [*Thorne and Andreoli*, 1980]), we cannot reach firm conclusions concerning the possible role of wave-particle interactions in general. However, it is useful to note that the highly bursty nature (i.e., short duration) of the precipitation events reported here would not be expected to be carried by EIC waves which usually do not exhibit a temporally discrete structure. In this same connection we note that wideband impulsive waves have been observed on ISEE 1 [*Reinleitner et al.*, 1983] and DE 1 satellites [*Sonwalkar et al.*, 1990] on L shells of $\sim 3.5 < L < \sim 12$. These impulses are observed near and outside the plasmapause, cover a very wide frequency range (typically from <500 Hz to >10 kHz), have durations of 100 ms to 1 s [*Sonwalkar et al.*, 1990], and have been shown to be associated with ELF/VLF chorus as observed on satellites [*Reinleitner et al.*, 1983]. Their highly impulsive nature and the fact that they extend to <500-Hz frequencies are consistent with the short duration of the relativistic microbursts; possible association between the relativistic microbursts reported here and the wideband impulsive waves needs to be further investigated, using in situ data on waves.

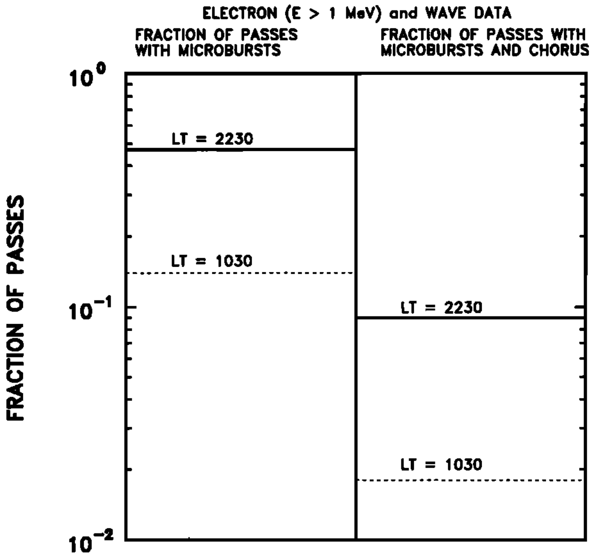

Fig. 11. The frequency of occurrence of the electron microbursts at two local times.

From the data presented here the following conclusions can be made in regard to the mechanisms responsible for the precipitation of microbursts of relativistic electrons:

1. Relativistic electron microbursts were observed more often near 2230 than near 1030 LT, a pattern distinctly different from the more favored occurrence of softer energy microbursts near the daytime hours.
2. As expected, based on considerations of gyroresonant energy and wave frequencies, relativistic electron microbursts were not accompanied by ELF/VLF chorus observed at ground stations during passes of the satellite overhead or near the conjugate point.
3. The relativistic electron microbursts at nighttime often occurred near the trapping boundary, consistent with spatial variations associated with geomagnetic field line irregularities.
4. Microbursts of relativistic electrons clearly have a different origin from low-energy microbursts. The underlying precipitation mechanisms may either involve electrostatic waves not observed on the ground or not involve wave-particle interactions.

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