JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 94, NO. A8, PAGES 10,079–10,093, AUGUST 1, 1989

Characteristics of Short-Duration Electron Precipitation Bursts and Their Relationship With VLF Wave Activity

W. L. IMHOF, H. D. VOSS, J. MOBILIA, AND M. WALT

Lockheed Palo Alto Research Laboratory, Palo Alto, California

U. S. INAN AND D. L. CARPENTER

STAR Laboratory, Stanford University, Stanford, California

Energetic (>6 keV) electron data from the SEEP payload on the low altitude (~200 km) polar orbiting S81-1 satellite indicate a high rate of occurrence of short duration (<0.6 s) electron precipitation bursts. Characteristics of events observed at night (2230 MLT) versus daytime (1030 MLT) and at midlatitudes ($2 < L < 3$) versus higher latitudes ($L > 3$) were distinctly different in several ways. For $2 < L < 3$ the daytime bursts occurred approximately uniformly in longitude and were equally distributed between the northern and southern hemispheres. The nighttime bursts in the same L shell range occurred approximately twice as often on a worldwide basis and were observed predominantly in the northern hemisphere and at longitudes of 260°E to 320°E. In a significant number of the nighttime events at $2 < L < 3$ the median electron energy increased with time during the burst, but most of the other spectra showed no well-defined trend. During some of the nighttime bursts broad peaks were observed in the energy spectra, but these peaks were not so evident in the daytime bursts. On higher L shells, $L > 3$, narrow electron precipitation bursts (<0.3 s duration) were frequently observed poleward of the plasmapause, more often near noon than near midnight and much more frequently than at $2 < L < 3$. Comparison of the electron data with simultaneous VLF wave data from Palmer ($L \simeq 2.4$) and Siple ($L \simeq 4.3$) stations in Antarctica indicated a varying degree of association of electron bursts with whistlers and chorus emissions. Several of the electron bursts observed at nighttime and at $2 < L < 3$ were correlated with lightning-generated whistlers observed at Palmer Station. When daytime bursts at higher latitudes ($L > 3$) were observed on satellite passes within ±50° of the Siple meridian, chorus was invariably detected at Siple, but correlation of electron bursts with individual chorus spectral elements was not evident. The lack of such correlation may be due to the limited spatial extent of flux tubes excited by individual chorus elements which are possibly generated without mutual coherence in multiple high altitude magnetospheric locations. Within one hour of all four of the satellite passes within 400 km of Siple with the highest rate (≥ 10 individual bursts per pass) of burst occurrence, overhead electron precipitation was clearly detected by ground based sensors at Siple Station. Quasi-periodic bursts of several seconds duration were observed on one or more of the photometer, riometer, and magnetic pulsation sensors and many of these bursts were correlated with clustered VLF chorus bursts. Hence, there is at least association of chorus with electron precipitation.

INTRODUCTION

In a recent paper, *Imhof et al.* [1986], we considered the contributions of various VLF wave types to the loss rates into the atmosphere of electrons trapped in the slot region of the radiation belts. From that investigation, as well as earlier comparisons between nighttime bursts and whistler activity [*Voss et al.*, 1984], it was suggested on the basis of the longitude and L shell variations that some of the well-defined bursts at nighttime were associated with lightning generated whistlers and some of those in the daytime may have been caused by other wave types such as chorus. However, the daytime electron precipitation events were not compared with simultaneous measurements of waves or with ground-observed signatures of particle precipitation, nor were many features of the electron precipitation such as the dynamic energy spectra and the time profiles intercompared between the daytime and nighttime events.

Over the years burst precipitation at mid and high latitudes and its association with wave activity has been studied from the perspectives of satellites and rockets and from the viewpoints of ground stations and balloons. On Injun 3, *Oliven and Gurnett* [1968] made simultaneous measurements of electron bursts (of duration less than one second) and VLF chorus emissions at high latitudes. They found that electron precipitation bursts were always accompanied by chorus, but chorus bursts were not always accompanied by electron precipitation bursts. It was not generally possible to find a one-to-one association between individual electron precipitation bursts and individual chorus emissions. In a more recent experiment precipitation events of electrons 0.63 to 20 keV lasting from 1 to 2 s were observed from the HILAT satellite and interpreted by *Hardy and Burke* [1987] as arising from the interaction of VLF waves (possibly chorus) with plasma sheet electrons.

With the SEEP payload on the S81-1 spacecraft, *Voss et al.* [1984] found one-to-one correspondence between a series of nighttime electron bursts in the northern hemisphere near $L = 2.5$ and a series of whistlers recorded at Palmer Station, Antarctica in the south. In rocket experiments, *Rycroft* [1973] recorded a burst of electron precipitation at the time of a two-hop whistler recorded nearby on the ground, and *Goldberg et al.* [1987] observed X ray bursts that were coincident with lightning detected by nearby ground stations.

Paper number 89JA00729.
0148-0227/89/89JA-00729$05.00

Burst precipitation associated with discrete waves such as whistlers or chorus has been detected at ground stations by photometers and radiowave receivers and on balloons by X ray detectors. For bursts inside the plasmasphere, the correlated waves have generally been lightning-associated whistlers, and the lightning-induced electron precipitation (LEP) events have been detected by observing perturbations (Trimpi effects) on subionospherically propagating VLF waves [e.g., *Helliwell et al.*, 1973; *Inan and Carpenter*, 1986, 1987]. Poleward of the plasmapause the waves have usually been VLF chorus emissions, some of which showed evidence of being triggered by whistlers. Correlated bursts of X rays and whistler-triggered chorus were observed at Siple Station, Antarctica ($L \simeq 4.3$) and were reported by *Rosenberg et al.* [1971] and by *Foster and Rosenberg* [1976]. Precipitating electrons with energies between ~70 and 250 keV were interpreted to be the primary contributors to the observed X ray flux. The typical VLF burst consisted of 3 to 5 rising elements of 0.1 seconds duration separated by ~0.15 s and was confined to the frequency range 1.5 to 3.8 kHz. In later experiments at $L = 4.3$ a detailed correlation was found in two events between electron microbursts and chorus elements of rising frequency observed at ionospheric conjugate points of the geomagnetic field [*Rosenberg et al.*, 1981]. Recently, the subionospheric signal from the Siple, Antarctica, experimental VLF transmitter received at several Antarctica stations has been used to detect wave-associated precipitation effects poleward of the plasmapause (*Carpenter et al.*, 1985; *Hurren et al.*, 1986].

To extend our understanding of the burst precipitation process, we have surveyed electron precipitation on a global basis and where possible compared the electron data with ground measurements of simultaneous wave activity and ionospheric effects. The present paper describes preliminary work of this kind, based upon electron measurements aboard the polar orbiting S81-1 satellite. Burst phenomena are studied both at midlatitudes (L = 2 to 3) and at higher L shells extending beyond the plasmapause. The temporal and energy spectral characteristics of nighttime and daytime bursts are investigated, and VLF wave data recorded at Siple and Palmer Stations in Antarctica are searched for wave activity that may be associated with the electron bursts.

DESCRIPTION OF INSTRUMENTATION

The stimulated emission of energetic particles (SEEP) experiment on the three-axis stabilized 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 until December 5, 1982. The S81-1 satellite was in a sun synchronous 1030 and 2230 local time polar orbit (inclination = 96.3°) at 170 to 280 km altitude, traveling southward during the daytime. The electron spectrometers were oriented at various angles to the local vertical. Data are presented from only two of the spectrometers. The spectrometer TE2 at 90° zenith angle (approximately 90° pitch angle for the data presented) had an acceptance angle of ±20° and a geometric factor of 0.17 cm^2 sr. The pulse-height analyzer for the data presented had a range of 6 to 930 keV with energy steps of 3.62 keV. The instrument ME1 at a zenith angle of 0° (approximately 30° pitch angle for most of the data presented) had an acceptance angle of ±30°, a geometric factor of 2.47 cm^2 sr, a threshold energy of 45 keV, and an energy resolution of about 20 keV. Total integral counting rates above several thresholds in each of the spectrometers were recorded during successive 0.064 second intervals, and the pulse height address of the first count in each successive 0.004-s interval was recorded for TE2 and for ME1.

In the data analysis L values were calculated using the Goddard Space Flight Center (GSFC 12/66) geomagnetic field model [*Cain et al.*, 1967] for the Epoch 1980.

OVERVIEW: ELECTRON BURSTS OBSERVED OVER A WIDE RANGE OF LATITUDES

Narrow bursts of electron precipitation with total durations of less than 0.6 s were observed in the SEEP experiment over a wide range of latitudes including L = 2 to 5. The latitudinal distribution of such bursts for a particular orbital pass is illustrated in the lower and middle panels of Figure 1. A strong and isolated electron precipitation burst was observed at $L = 2.47$, equatorward of the plasmapause, which at this time was estimated to have been at $L = 3.6$ from ground-based whistler data. At $L \simeq 2.8$ there were some weaker events, but otherwise no strong burst activity until $L \simeq 3.6$, beyond which burst activity substantially increased. Bursts were detected frequently, at time separations of less than 10 s. In this and many other satellite passes on which short bursts were observed, electron burst activity was concentrated above a well-defined L value near $L = 4$ which we associate with the plasmapause or its near vicinity in the poleward direction.

Throughout the SEEP pass illustrated in Figure 1, Siple Station ($L \simeq 4.3$, 76°S, 276°E) recorded strong chorus emissions in the band ~0.5 to 1.5 kHz. Spectrograms of the wave activity during subintervals are shown at the top of Figure 1; they are restricted to 2-s recording intervals between 3-s pulses from the Siple Station experimental VLF transmitter. One-to-one correlations between the electron bursts at $L > 3.6$ and chorus structure were not observed. Such correlations were not necessarily expected, in view of the substantial longitude separation of the spacecraft and ground station (~26° or ~700 km at $L \sim 4.3$) and the fact that only a subset of magnetospheric chorus waves (i.e., ducted signals) are observed on the ground. Whistler propagation to Palmer Station ($L \sim 2.4$, 65°S, 296°E) was observed at rates of 20 to 40 per minute during synoptic recordings that both preceded and followed the SEEP pass. The satellite track at $L = 2.5$ was ~1100 km to the east of Palmer, and while no ground recording was made during the overpass, a causal relation between whistlers and the burst activity at $L = 2.47$ and near $L = 2.8$ is considered likely.

ELECTRON PRECIPITATION BURSTS AT MID-LATITUDES

In the midlatitude range, L = 2 to 3, daytime and nighttime bursts were identified by the following selection criterion: a factor of 2 increase in the integral (>45 keV) flux observed with both the ME1 detector (at 0° zenith angle) and the TE2 detector (at 90° zenith angle) and a total pulse length (full-width-at-half maximum, including rise time, width, and decay) of less than 0.6 s. (Many "weaker" bursts and longer bursts were observed, but they are not considered here). Multiple bursts with a repetition period of a few tenths of a second were considered part of the same event. To be classified as distinct events, pulses had to be separated by

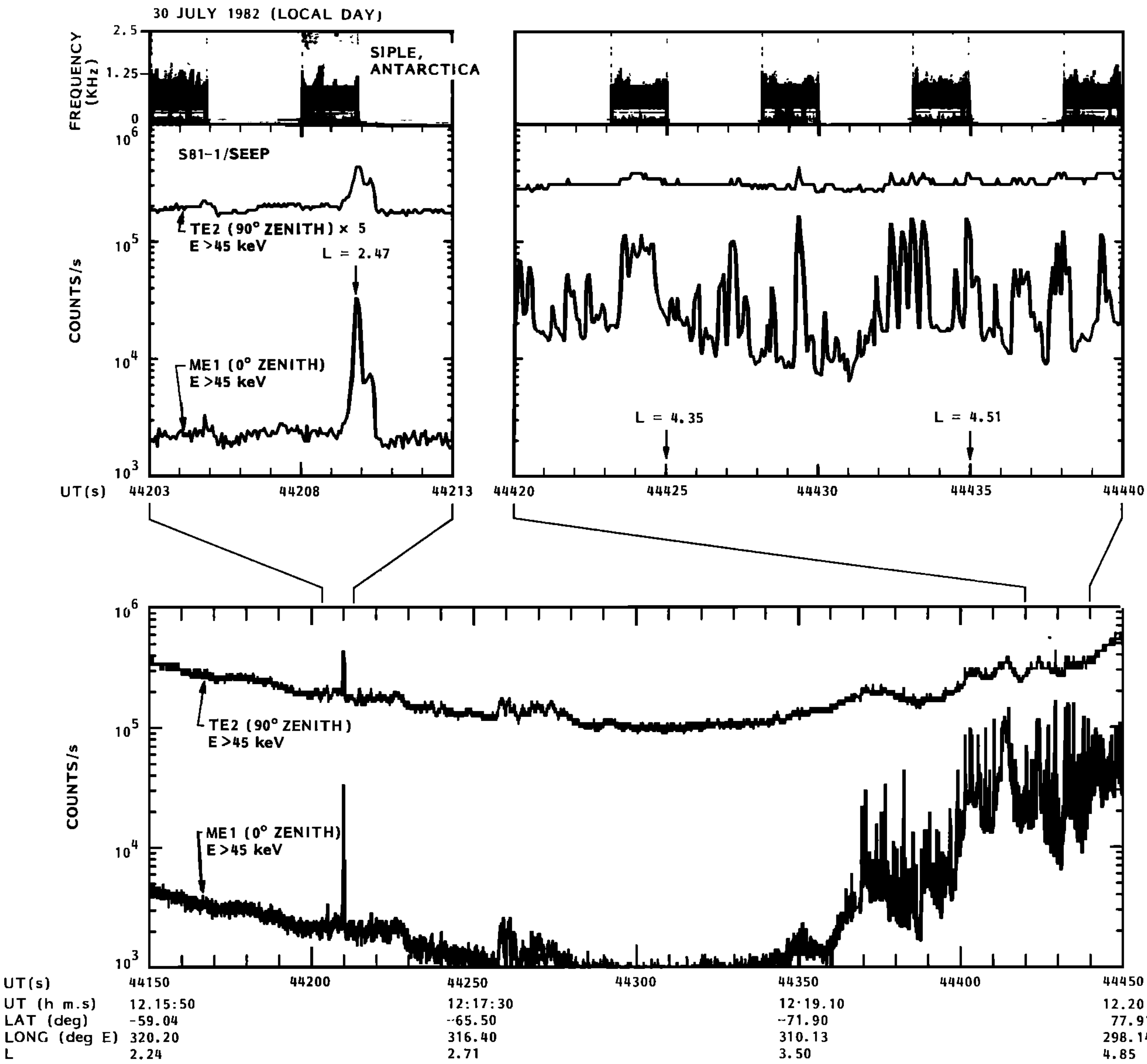

Fig. 1. Counting rate versus time for the ME1 (>45 keV) and TE2 (>45 keV) detectors during a daytime pass of the S81-1 satellite. Also shown is the frequency-time record acquired at Siple Station. Nonrecording times are blank.

more than 7 s. With such criteria at mid-latitudes, 59 events at night and 26 in the daytime were found from the 6-month data set. With a broader criterion, one second rise time and 3-second decay time, 222 electron bursts at L = 2 to 3 had been selected [*Imhof et al.*, 1986] from this data set which had a comparable number of daytime (4854) and nighttime (4773) satellite passes.

As an example the detailed time and energy characteristics of a nighttime burst at $L = 2.27$ are presented in Figure 2. The counting rates versus time are shown in the left-hand section for the ME1 and TE2 detectors for $E > 45$ keV. The listed start time of the plot is chosen to place the peak of the burst in the 90° detector at $t = 1$ second. In the right-hand section of Figure 2, the energies of individual electrons sampled by the TE2 detector at a maximum rate of one during each 0.004 s are plotted as a function of time for those periods when the counting rate was significantly above background. In addition, median energies are plotted as squares for each 0.064-s interval, and these squares are connected with straight lines.

The characteristics of eight representative bursts (four at night and four in the daytime) at $2 < L < 3$ are presented in Figure 3 with the same format as the previous figure. In the spectral presentations only the median energies for each 0.064 second interval are shown. The times and coordinates of the satellite during each of the observations are indicated. In these nighttime events an initial peak in the TE2 detector is followed by subsequent peaks separated by about 0.5 s. These peaks are believed to be due to multiple bounces (between hemispheres) of the electrons that have first interacted with the waves and then backscattered from the atmosphere [*Voss et al.*, 1984]. In these plots the evidence for multiple bounces between hemispheres is stronger at night than during the day. Typically, for the nighttime bursts the counting rate in the ME1 spectrometer at 0° zenith angle is very weak on the first pulse in comparison to the TE2 detector near 90° pitch angle or to subsequent pulses in the ME1 spectrometer. This effect is discussed in more detail by *Voss et al.* [1984] and is attributed to changes in the electron

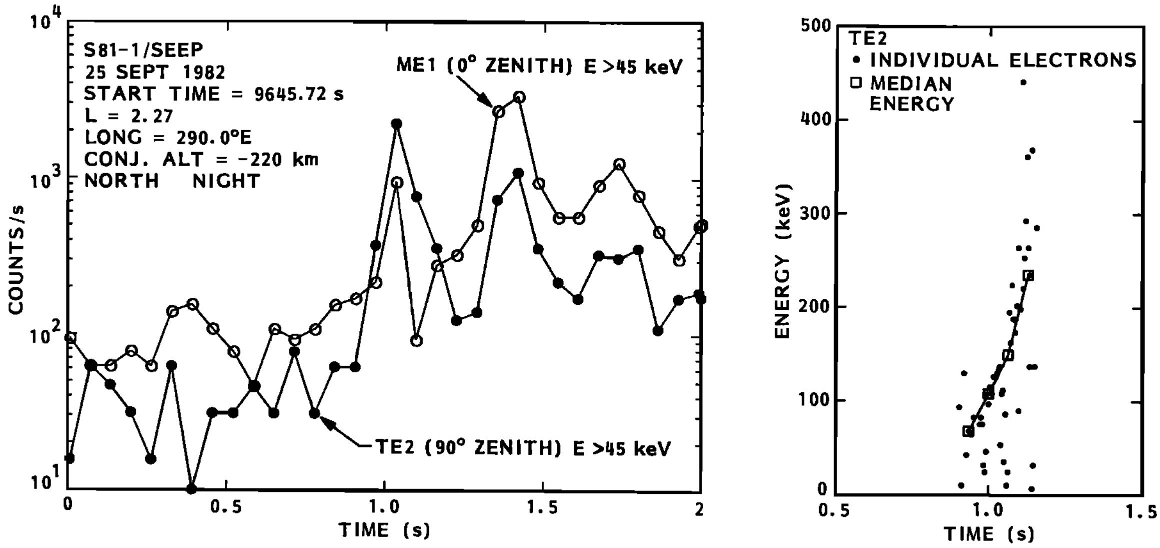

Fig. 2. Data from a representative isolated night burst. In the left-hand section is shown the counting rate versus time for the ME1 and TE2 detectors. In the right-hand section are shown the energies of individual electron counts and median energies during 0.064-s intervals in the TE2 detector.

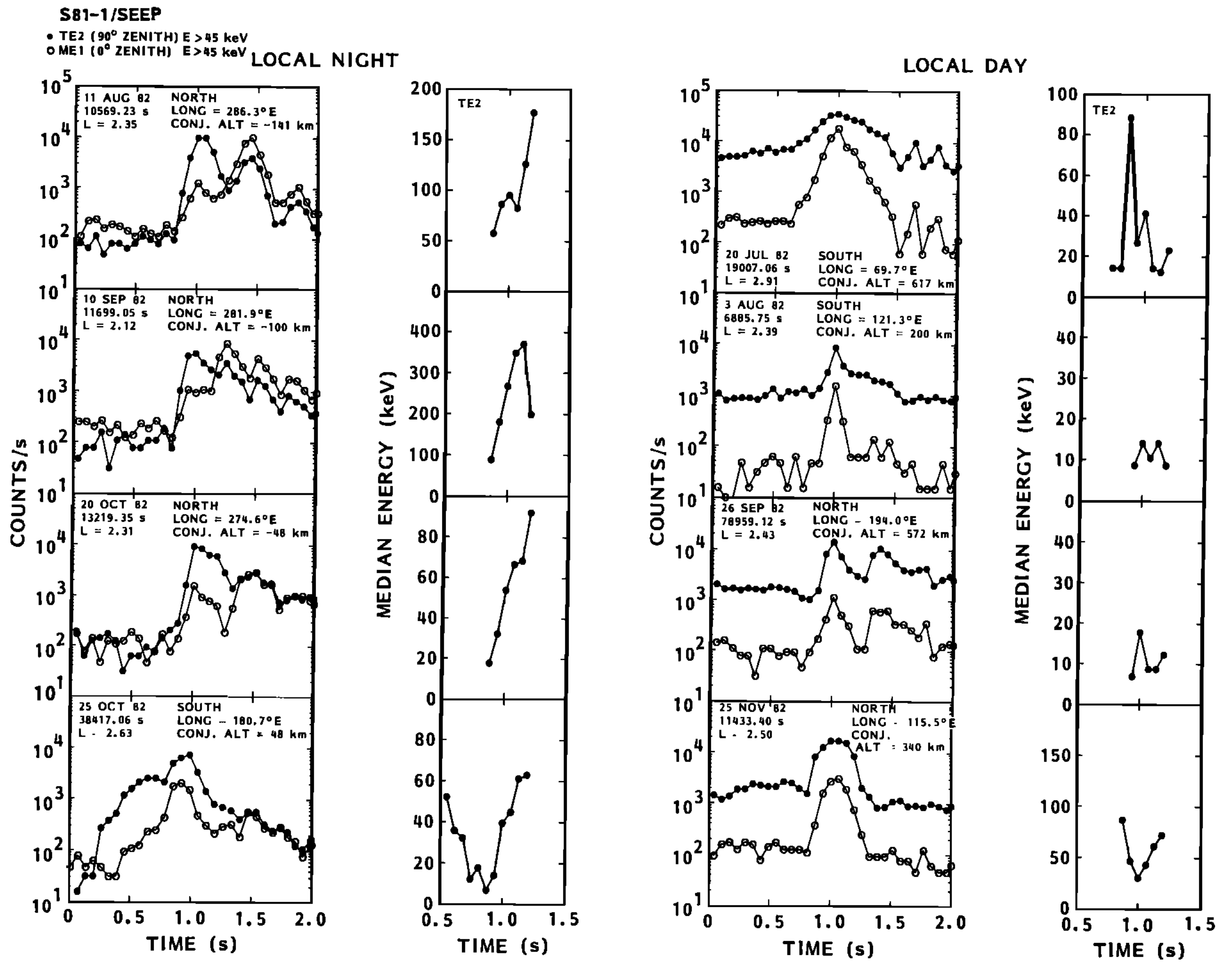

Fig. 3. Data from representative isolated night and day bursts at L = 2 to 3. In the left-hand section is shown counting rate versus time for the ME1 and TE2 detectors. In the right-hand sections are shown the median energies during 0.064-s intervals in the TE2 detector.

TABLE 1. Spectral Trends With Time for Narrow Bursts at $2 < L < 3$

Median Energy Trends With Time During the Burst	Number of Daytime Cases	Number of Nighttime Cases
Rises	0	18
Falls	4	2
Falls, then rises	1	5
Rises, then falls	2	1
Not well defined	19	33
Total	26	59

pitch angle distribution when the initial pulse is reflected by atmospheric scattering.

In the right-hand portion of each panel in Figure 3 the median energies are plotted as a function of time beginning when the counting rate was significantly above background and extending for 0.192 s after occurrence of the peak flux. At nighttime the median energy often tended to increase with time during the first pulse. This behavior occurred in the examples shown in the left-hand section of the figure, except for the October 25 case in which an unusually prolonged rise time perhaps unrelated to the burst itself, displayed a decreasing average energy. A detailed interpretation of the common trend, associated with the time variation of wave frequency in whistlers, is discussed by *Inan et al.* [1989]. Most of the daytime events (right-hand panels) showed little systematic spectral variation with time during the burst. A summary of the spectral trends with time during each of the 85 bursts reported here is given in Table 1. The trends were obtained by visual inspection and are listed as not well defined unless a clear-cut slope associated with the enhanced flux was apparent. Many of the "not well defined" cases can be attributed solely to the relatively low counting rate increase during the burst.

The time-integrated energy spectra of the electrons recorded during a 0.64 second interval spanning representative nightside and dayside bursts are shown in Figure 4. Background counting rates in each channel, taken to be equal to the rate preceding the burst, have been subtracted. In order to reduce the statistical scatter the 3.62-keV-wide energy channels are grouped by fives. A broad peak sometimes

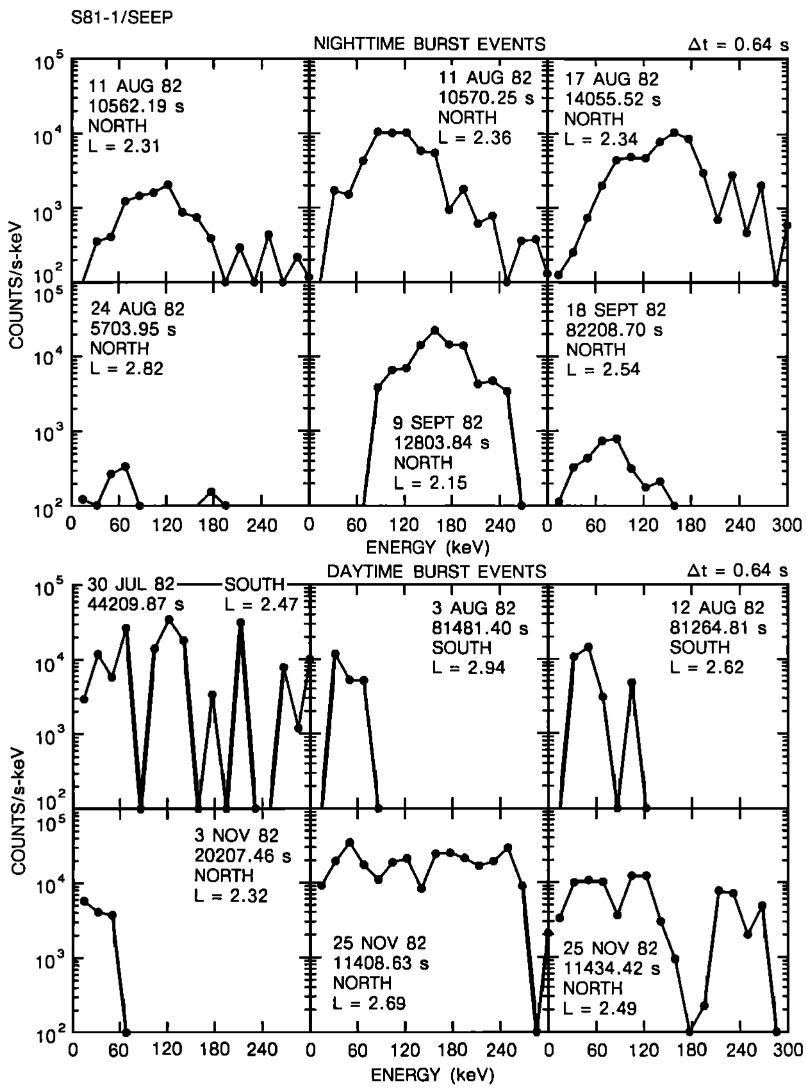

Fig. 4. Representative energy spectra measured during 0.64-s intervals in the TE2 detector for isolated nighttime and daytime electron bursts. The times listed are UT (s) start times for the intervals.

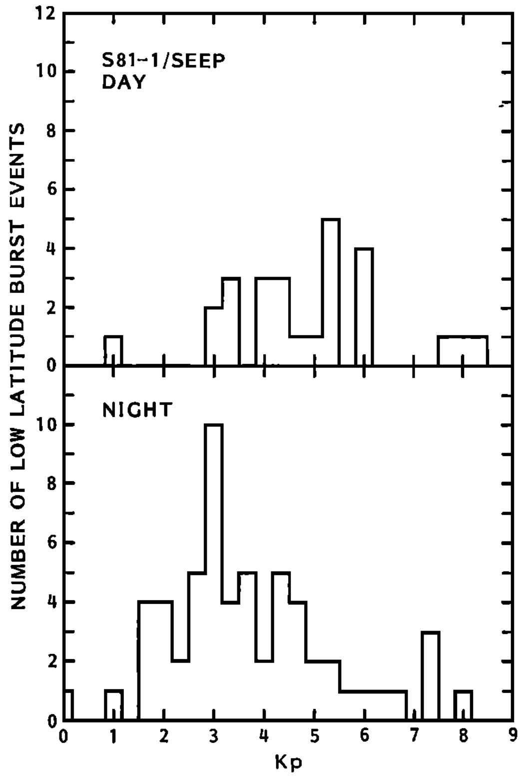

Fig. 5. The distributions in Kp values for the bursts at $L = 2$ to 3.

appears in the nightside energy spectra, but peaks are not so evident in the daytime spectra. The electron energies involved are generally consistent with those expected to arise from equatorial gyroresonant interactions within the plasmasphere with whistlers or outside the plasmapause with either whistlers or chorus emissions at frequencies up to a few kHz.

Histograms of the geomagnetic activity conditions (Kp) under which the dayside and nightside bursts at $L = 2$ to 3 were observed are presented in Figure 5. The occurrence of nightside events follows approximately the probability of occurrence of various Kp levels. In contrast, the daytime events show a tendency to occur with greater probability as disturbance levels increase from moderate to severe. A statistical comparison of the day and night distributions using the U-test of Wilcoxon, Mann, and Whitney shows that these two distributions are different, the probability that they are samples drawn from a common distribution being 0.005.

The L shell and longitude locations of the burst observations are presented in Figure 6 for each of the events at $2 < L < 3$. The daytime and nighttime events are plotted with open and closed circles, respectively. The coverage at the two local times was approximately equal, and a comparable number of passes was obtained at each longitude and L shell. As noted above, narrow bursts were identified only about half as often in the daytime as at night. The higher rate of event occurrence at night may result from increased ionospheric (D region) absorption during daytime at VLF frequencies [*Helliwell*, 1965]. Due to this effect, whistler wave intensities in the magnetosphere would be expected to be higher at night than during day thus leading to generally higher precipitation fluxes. The nighttime events were concentrated in the north at 260°E to 320°E longitude. This concentration is probably due to several factors, such as the distribution of lightning activity and the proximity of the South Atlantic Anomaly. The latter has the effect of reducing the flux normally present at the satellite altitude and allows small flux increases to satisfy the selection criteria. The east coast of the United States is a known region of high thunderstorm activity [*Turman and Edgar*, 1982; *Mobilia et al.*, 1985; *Orville and Henderson*, 1986], and this concentration of lightning flashes would lead to more electron burst events in this region at nighttime. However, ground-based observations of ionospheric effects of LEP bursts indicate a high level of event occurrence at longitudes of the western United States (e.g., 240°E to 260°E) [*Inan et al.*, 1988].

In the nighttime ground-based measurements of ionospheric effects of LEP events also suggest that a comparatively high rate of events and generally larger fluxes should occur in the southern hemisphere near the longitudes of the South Atlantic Anomaly [*Inan et al.*, 1988]. The relatively small number of nighttime events observed in the south at 260°E to 320°E longitude can primarily be attributed to larger background fluxes of trapped electrons near the South Atlantic Anomaly and to the somewhat higher altitudes of the satellite in the southern hemisphere. We note that measurements of ionospheric effects are sensitive only to precipitating electrons while the sensitivity of the satellite-

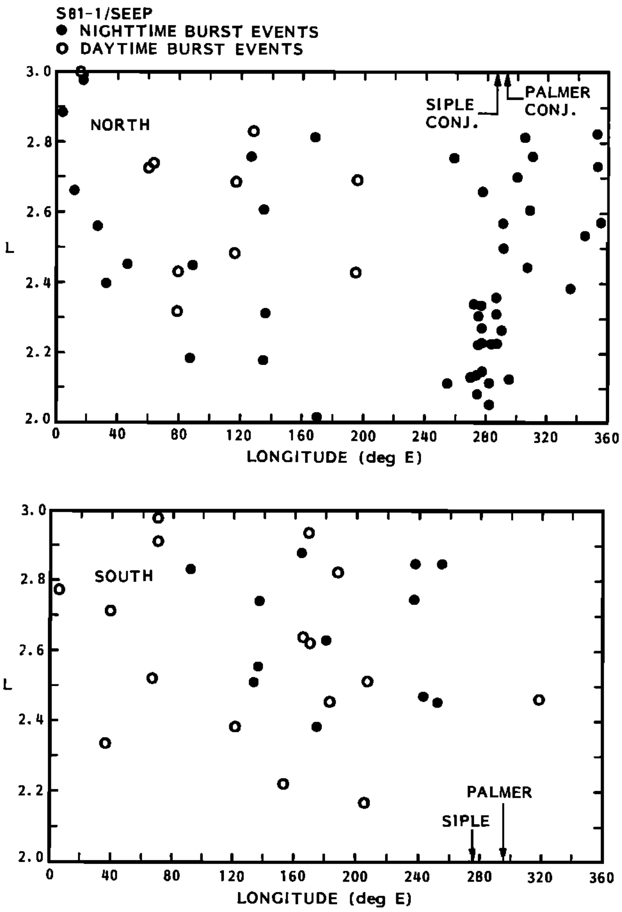

Fig. 6. The longitude and L shell locations of each of the narrow bursts at $L = 2$ to 3 in the northern and southern hemispheres. The meridians of Siple and Palmer stations and their conjugate points are indicated.

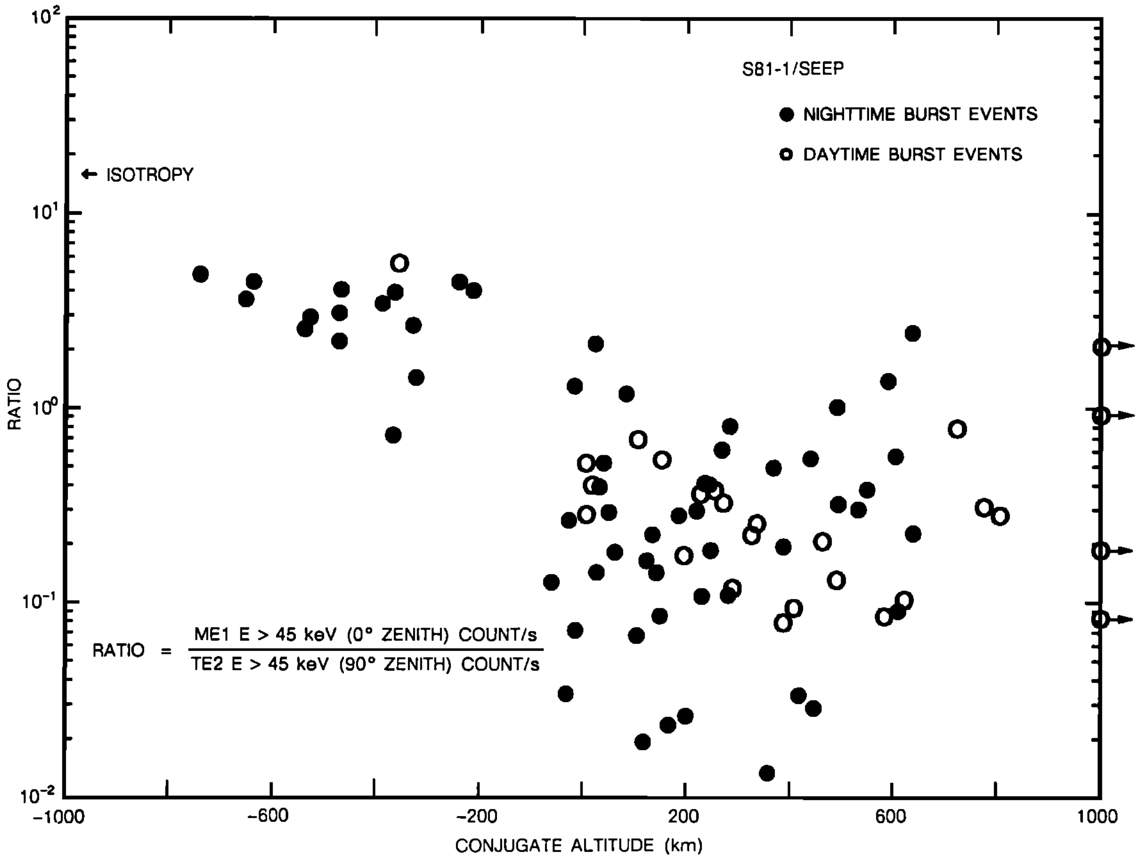

Fig. 7. Ratio of the net counting rate (with preburst rate subtracted) in the ME1 detector to that in the TE2 detector, plotted as a function of the altitude of the conjugate point. The ME1 spectrometer is at a zenith angle of 0° and typical pitch angle of ~30°. For the TE2 spectrometer these angles are 90° and ~90°. The ratio of counting rates for isotropy is indicated.

based burst detection also depends on the background of trapped flux. Our data also suggest a somewhat higher nighttime rate of occurrence in the south in the longitude range of 120°E to 260°E. The reasons for this effect are not known and statistics are not sufficient for any definitive conclusions. In contrast to the nighttime bursts, the daytime events display a slight preference for occurrence in the southern hemisphere but indicate no significant longitude variations within the limited statistical accuracies.

Let us next consider the pitch angle distributions associated with the electron precipitation bursts at different locations. A simple and convenient parameter representing the pitch angle distribution is the ratio of net counting rate (with preburst rate subtracted) in the ME1 detector (at ~30° pitch angle) to that in the TE2 detector (at ~90° pitch angle). Since one would expect this ratio to be influenced by the local atmospheric loss cone, the ratios are sorted by conjugate altitude, separately for day and night local times. The ratios are shown in Figure 7 during the 0.064-s interval at the time of the peak counting rate in the TE2 detector; they are plotted as a function of the conjugate point altitude. The ratio for pitch angle isotropy allowing for differences in the geometric factors of the two detectors is indicated. The ratios show considerable scatter but tend to decrease with increasing altitude of the conjugate point, and for large negative values of the altitude at the conjugate point the ME1/TE2 ratios indicate a more isotropic distribution. Even under the latter conditions the ratios are still less than those corresponding to isotropy, or equivalently the pitch angle distributions show less flux near 30° than 90°. The variation of the pitch angle distribution with altitude of the conjugate point is similar for both daytime and nighttime events; this result may reflect the importance of atmospheric effects at both local times rather than any similarity in the precipitation mechanism.

It has not been possible to sort all of the daytime $L = 2$ to 3 events with respect to plasmapause location. The results of earlier studies of plasmapause radius as a function of geomagnetic activity [*Carpenter and Park*, 1973] suggest that the plasmapause was at $L < 3$ during some of the burst observations that occurred under relatively disturbed conditions. However, it is likely that a significant fraction of the daytime bursts occurred within the plasmasphere, as illustrated above for the case of Figure 1.

Most of the nightside events are believed to have occurred within the plasmasphere, based on considerations of magnetic activity (and in individual cases upon analyses of the correlated whistlers [e.g., *Voss et al.*, 1984]). This inference is supported by the lower disturbance levels associated with these cases, and the fact that the plasmasphere radius at ~2230 MLT is on the average larger than it is in the post-dawn sector, where it tends to be near a diurnal minimum [*Carpenter*, 1966].

Electron Precipitation Bursts at High Latitudes

At $L > 3$ narrow electron precipitation bursts were detected much more frequently than at $L < 3$. Accordingly, an initial study was made of 87 satellite passes (61 in daytime,

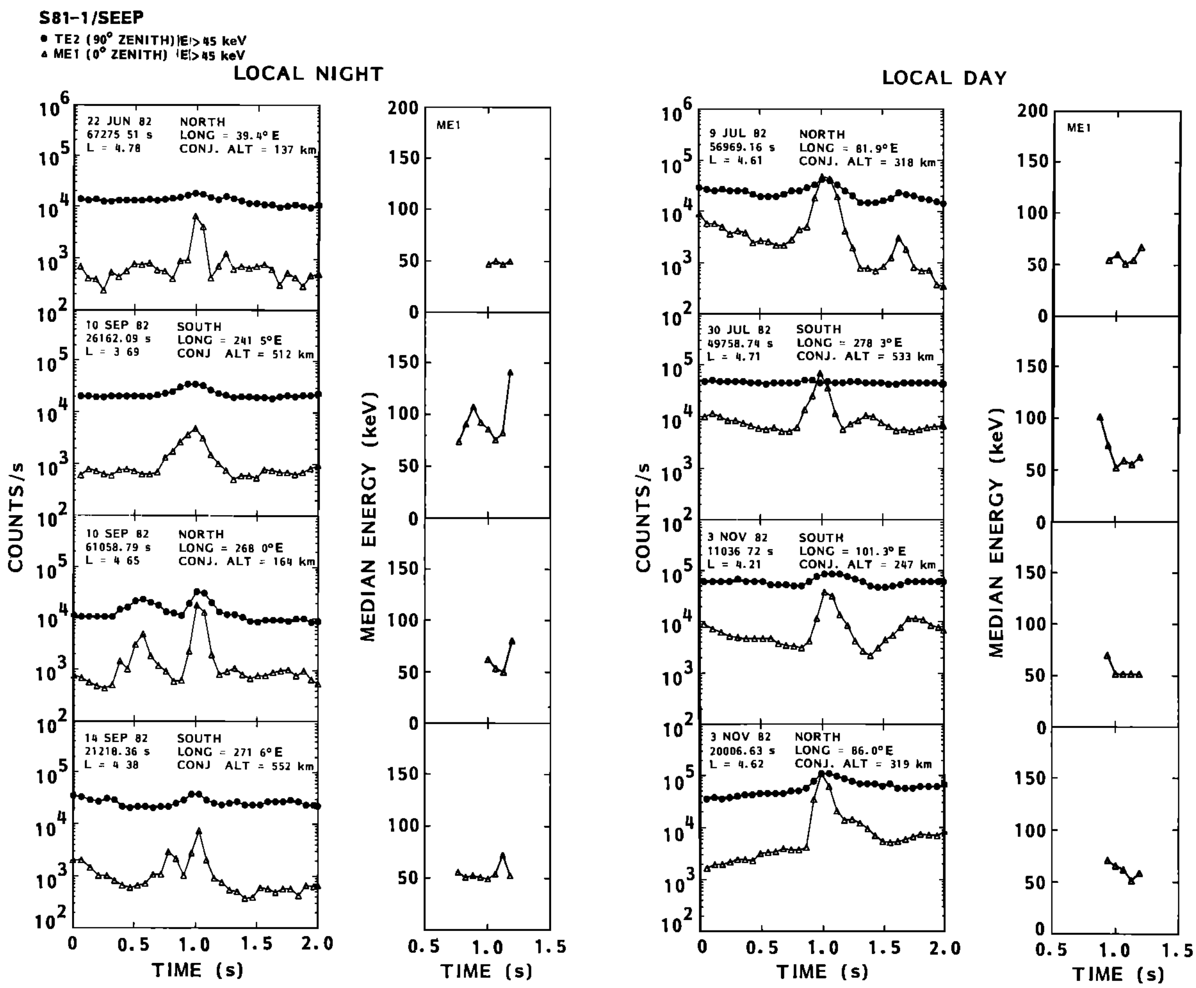

Fig. 8. Data from representative night and day bursts at $L = 4$ to 5. In the left hand sections are shown counting rate versus time for the ME1 and TE2 detectors. In the right-hand sections are shown median energies during 0.064-s intervals in the ME1 detector.

26 at night) from the period of May 28 to December 5, 1982. Many of the passes studied were processed because the satellite passed near (within $\pm 10°$) the meridians of Siple or Palmer station, (276°E and 296°E, respectively), but otherwise there was no special selection criterion. Narrow bursts at $L > 3$ were identified by the criterion that the ME1 detector show a counting rate increase of at least a factor of 2, that it be above 10^3 counts/second, and that the full width at half maximum of the counting rate peak be less than or equal to 0.3 s. No restrictions were placed on the appearance of another burst nearby in time.

Time profiles of the counting rates and median energies for peaks occurring at $L \sim 4$ to 5 are shown in Figure 8 for several dayside and nightside bursts. The listed start times of the plots are chosen to place the peak of the burst in the ME1 detector at $t = 1$ s. The energy spectra were taken from the ME1 spectrometer, since the events were much more prominent in that detector than in the TE2 spectrometer. In the ME1 detector individual pulse height addresses were recorded at a maximum rate of 16 per 0.064 s as with the TE2 detector. As in Figure 4, energy points are shown at times beginning when the counting rate was significantly above background and extending for three time frames (0.192 s) after the peak flux, provided that the counting rate in the ME1 spectrometer was significantly above background. No consistent trend with time is evident in the median energies.

On 58 of 87 satellite passes, one or more narrow bursts were found at $L = 3$ to 5. The frequent clustering of bursts above some L value was indicated in Figure 1 and is further illustrated for day and night passes in Figure 9, where the counting rates in the ME1 detector are plotted as a function of time. On the top pair of panels, low L values are at the center of the page. In the daytime example at left, bursts are seen as narrow spikes extending above an envelope that drops sharply, by about an order of magnitude at $L \simeq 3.5$, after which the count rate is low and steady. In the night example neither narrow bursts nor elevated counts at higher L were observed. In the middle pair of panels, higher L values are at the center of the page. Both passes show a relatively clear transition to a region of higher count rate and narrow burst activity at $L > \sim 3.4$. For both panels at the bottom of Figure 9, higher L is at the right. In the dayside case, an abrupt transition to strong burst activity occurs at $L \simeq 4$, while the nightside case shows a complex structure throughout. Note, particularly in the middle and lower panels the tendency for narrow spikes to be superimposed upon or otherwise accompany fluctuations with time durations near 10 s.

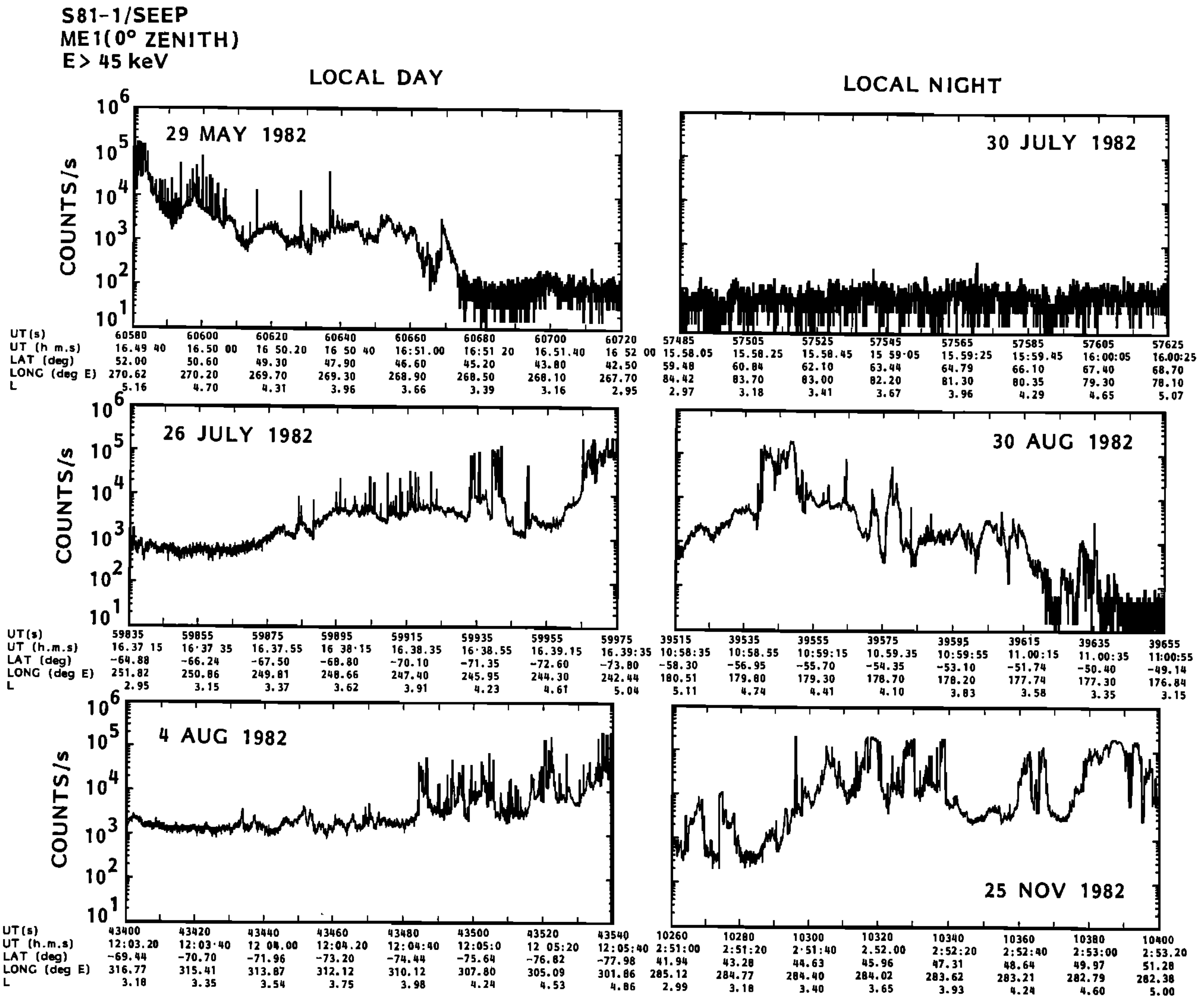

Fig. 9. Counting rate versus time for the ME1 (>45 keV) detector during various passes of the S81-1 satellite.

Figures 10*a* and 10*b* show by solid dots the *L* values of bursts on those 44 of 61 passes on the dayside and 14 of 26 at night, respectively, during which at least one narrow burst was observed at $L = 3$ to 5. The times in seconds and longitudes for crossing $L = 4$ are given. The average frequency of occurrence of daytime bursts increased rapidly between $L = 3.5$ and 4. At night the distribution was more uniform, but Figure 10*b* suggests that this finding was dominated by a single case (November 25, illustrated at lower right in Figure 9). The comparatively higher levels of activity on the dayside are believed to be associated with the morningside peak in chorus activity in the magnetosphere [*Burton and Holzer*, 1974; *Burtis and Helliwell*, 1976].

SIMULTANEOUS WAVE MEASUREMENTS AND ELECTRON BURSTS

A substantial number of continuous ground recordings were made at Siple and Palmer, Antarctica, stations during SEEP passes at nearby longitudes. Unfortunately, many of the Siple recordings were only available for 2 s out of every 5 during times when the transmitter was off, as illustrated in Figure 1, and at Palmer there were few simultaneous recordings during dayside passes. However, in the case of nightside satellite observations at $L = 2$ to 3, a number of recordings were made at Palmer ($L \simeq 2.4$), and cases have previously been found in which whistlers occurred in close time coincidence with the electron bursts in the $L = 2$ to 3 range [*Voss et al.*, 1984; *McNerney et al.*, 1987]. An example occurred on September 9, 1982 and was presented by *Voss et al.* [1984]. Another example, from October 20, 1982, is shown in Figure 11. The upper two panels show the 0 to 10 kHz dynamic spectrum and 2 to 3 kHz log amplitude of the VLF wave activity at Siple. As in the case reported by *Voss et al.* [1984], the satellite was in the northern hemisphere and at a longitude roughly 1600 km to the west of the conjugate point to Palmer Station. Arrows beneath the wave amplitude records show the times of the radio atmospherics of the lightning discharges for the five prominent whistlers, each of which preceded a surge in the electron count rate by ~0.5 s.

In the daytime, only one electron burst event at $L = 2$ to 3 was recorded near the meridian of Palmer Station or its conjugate, as indicated in Figure 6. This event, illustrated in Figure 1, occurred during a period when whistlers propagating in the L range 2.8 to 3.0 were recorded at rates of 20 to

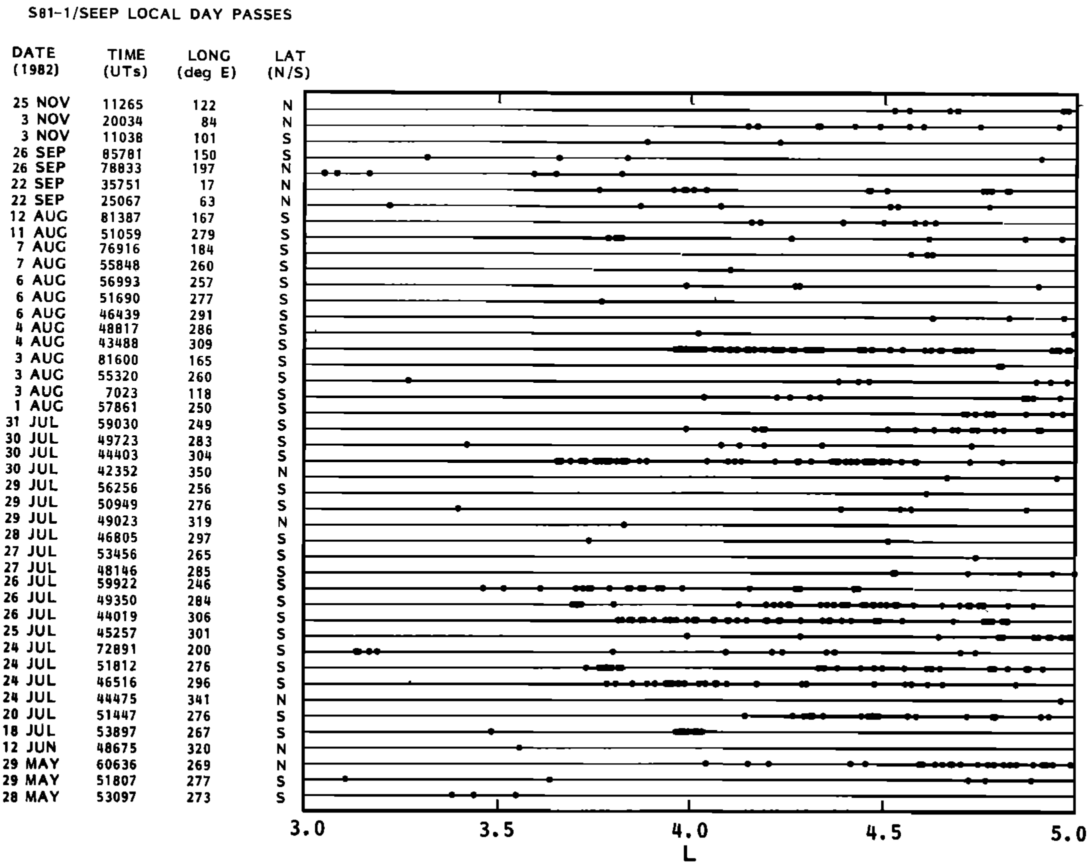

Fig. 10*a*. Each narrow burst with a time width of 0.3 s or less plotted as a function of L during each of several orbits in which at least one narrow burst was observed over the range $L = 3$ to 5.

40 per minute at Palmer Station. It is likely that the weak burst events in Figure 1 near $L = 2.8$ were associated with this ducted whistler activity, and that the burst at $L = 2.47$ was induced by a particularly strong whistler component which propagated on a nonducted path originating close to a source lightning discharge.

The nightside and dayside particle observations at $L > 3$ were supported by a number of simultaneous wave recordings at Siple. Of 40 passes within ±50° of the Siple meridian on which one or more narrow bursts (<0.3 s) were detected, simultaneous ground recordings either continuous or on a 2 s out of 5 s basis were available during 17. For the remaining 23 passes, 1-min synoptic recordings either continuous or on a 2 s out of 5 s basis were available within several minutes of the SEEP pass. Thirty-three of the forty passes were on the dayside, and during or near each of these, chorus activity was observed at Siple. An example is that of Figure 1, in which discrete chorus elements appear against a relatively continuous band of background noise.

In many of the 33 dayside cases there was also whistler activity, with triggering of chorus bursts in the 1 to 4 kHz range by whistler components propagating outside the plasmapause. This type of spectral record is interpreted as evidence that the plasmapause L value was equatorward of

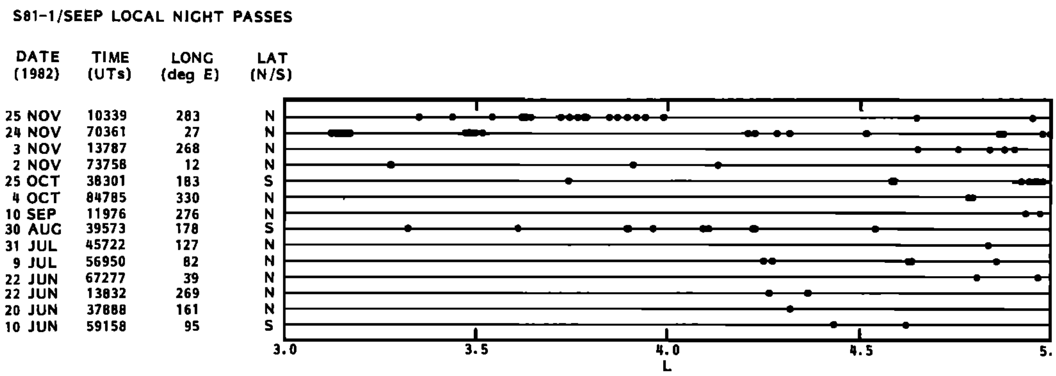

Fig. 10*b*. Each narrow burst with a time width of 0.3 s or less plotted as a function of L during each of several orbits in which at least one narrow burst was observed over the range $L = 3$ to 5.

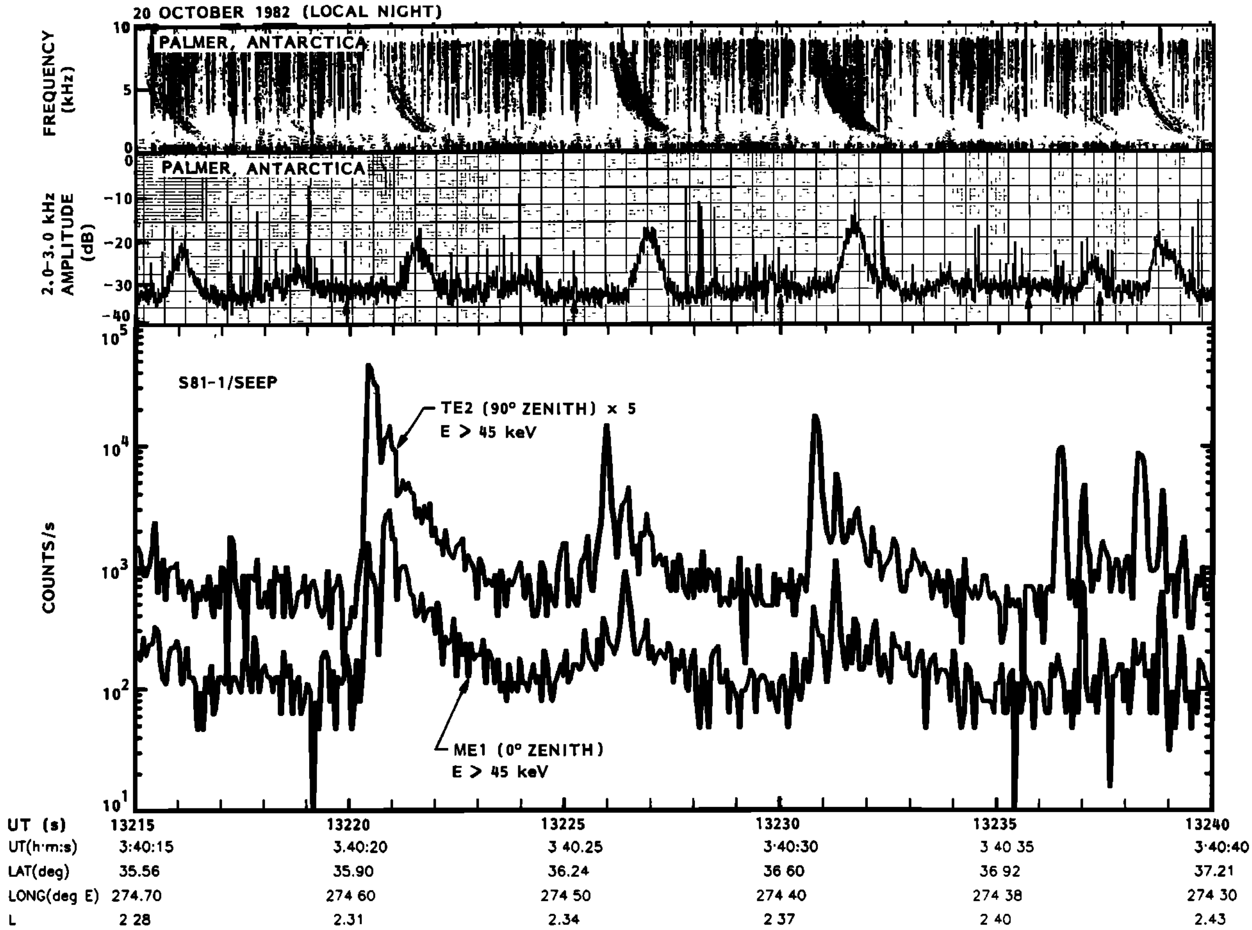

Fig. 11. In the top sections are shown the frequency-time record and the integrated wave intensity as recorded at Palmer Station. Arrows beneath the wave amplitude records show the times of the causative atmospherics of the five principal whistlers. In the bottom section the counting rates in the ME1 (>45 keV) detector at 0° zenith angle and the TE2 (>45 keV) detector at 90° zenith angle are plotted as a function of time. Ephemeris information for the satellite pass is provided at the bottom of the figure.

Siple [e.g., *Helliwell et al.*, 1980], as it was found to be for the pass of Figure 1. Both the dispersion properties of the whistlers surveyed and the high *Kp* levels associated with many of the dayside passes suggest that in most of these cases, the plasmapause was actually at $L < 4$ [e.g., *Carpenter*, 1966; *Carpenter and Park*, 1973]. Thus, the bulk of the narrow electron bursts observed on the dayside at $L > 3$ are inferred to have occurred poleward of the plasmapause and in the low density region where chorus is a major form of natural wave activity [*Burtis and Helliwell*, 1976].

For reasons discussed below, it was not anticipated that the individual chorus waves associated with electron bursts would be readily identifiable on ground records. In fact, such an identification was not achieved in the 17 cases for which simultaneous wave and particle data were available. Figure 12 shows the electron precipitation data from a dayside pass close to Siple (within ~2° at $L = 4.3$). The simultaneous 0 to 5 kHz VLF spectrum at Siple is illustrated in 2-s segments, showing two active frequency bands and numerous discrete rising chorus elements. Also shown is an amplitude record representing integrated field strength in a 300-Hz band centered at 1.5 kHz. A one-to-one correlation between chorus peaks and electron bursts is not evident, but the durations in time of the VLF amplitude enhancements are comparable to those of the electron bursts.

To illustrate the complex relations between the wave and electron data during the 40 passes within ±50° of the Siple meridian, we show in Figure 13 and 14 two of the four cases when continuous ground VLF recordings at Siple (a synoptic record of 53-s duration), were available during the satellite pass.

Figure 13 shows a dayside case in which the satellite crossed $L = 4.3$ about 20° east of Siple (~540 km). High burst activity was observed on the satellite, while the wave activity included pulsating (~10 s) clusters of chorus elements within a band below ~1 kHz and sporadic 2 to 3 kHz bursts, some of which were found to be triggered by whistlers.

Figure 14 shows another dayside case from ~20° west of Siple. In this case there was a prominent band near 1 kHz with many associated rising elements. Many of these risers appear to be part of a less steady higher-frequency band at 2.5 kHz.

While one-to-one correlations of narrow electron bursts with ground observed waves proved elusive, a close relation appears to have existed between a high rate of narrow bursts on the satellite at $L > 3$ in daytime and the observation of precipitation-induced ionospheric perturbations overhead Siple of the type reported previously by *Rosenberg et al.* [1971], *Helliwell et al.* [1980], and *Arnoldy et al.* [1982]. In

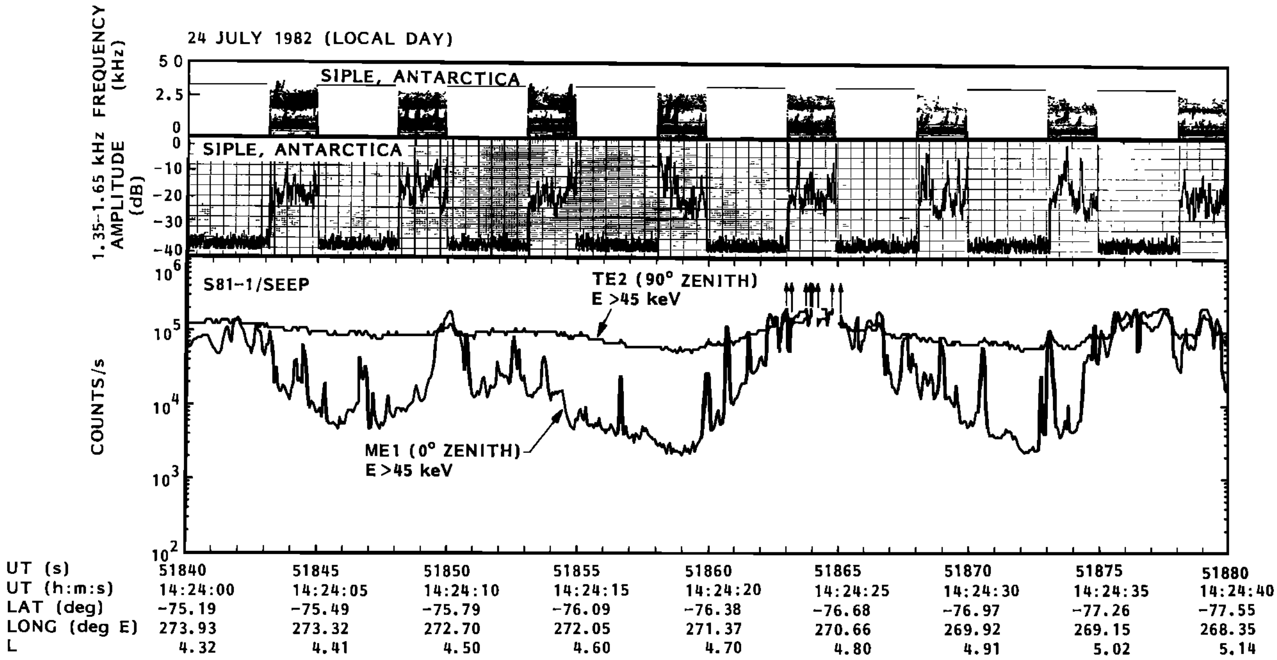

Fig. 12. In the top sections are shown the frequency-time record and the integrated wave intensity as recorded at Siple Station. In the bottom section the counting rates in the ME1 (>45 keV) detector at 0° zenith angle and the TE2 (>45 keV) detector at 90° zenith angle are plotted as a function of time.

ground records of photometers, riometers, wave magnetometers, and VLF receivers, this precipitation often appears in the form of quasi-periodic pulsations lasting from one to several seconds and separated by 5 to 30 s. On several occasions, such pulsations have been clearly linked to burstlike clusters of VLF chorus elements, some of which were triggered by whistlers [*Rosenberg et al.*, 1971; *Helliwell et al.*, 1980], and a few case studies have shown a link between the fine structure within multielement chorus bursts and X ray microbursts [*Rosenberg et al.*, 1981], as well as a connection between individual chorus elements and brief (<1 s) optical pulsations [*Tsuruda et al.*, 1981].

During 9 of the 61 dayside passes studied, the satellite was in the southern hemisphere and crossed $L = 4$ within ~8° or less

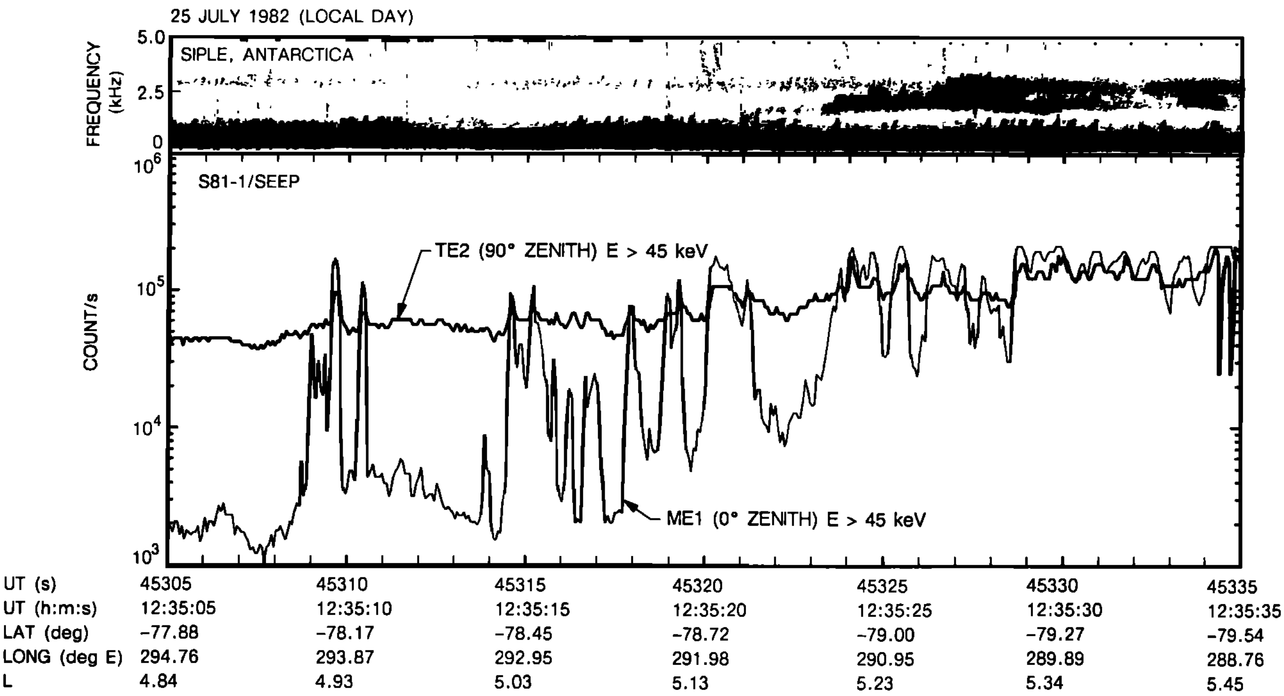

Fig. 13. In the upper section is shown the frequency-time record as recorded at Siple Station. In the bottom section the counting rates in the ME1 (>45 keV) detector at 0° zenith angle and the TE2 (>45 keV) detector at 90° zenith angle are plotted as a function of time.

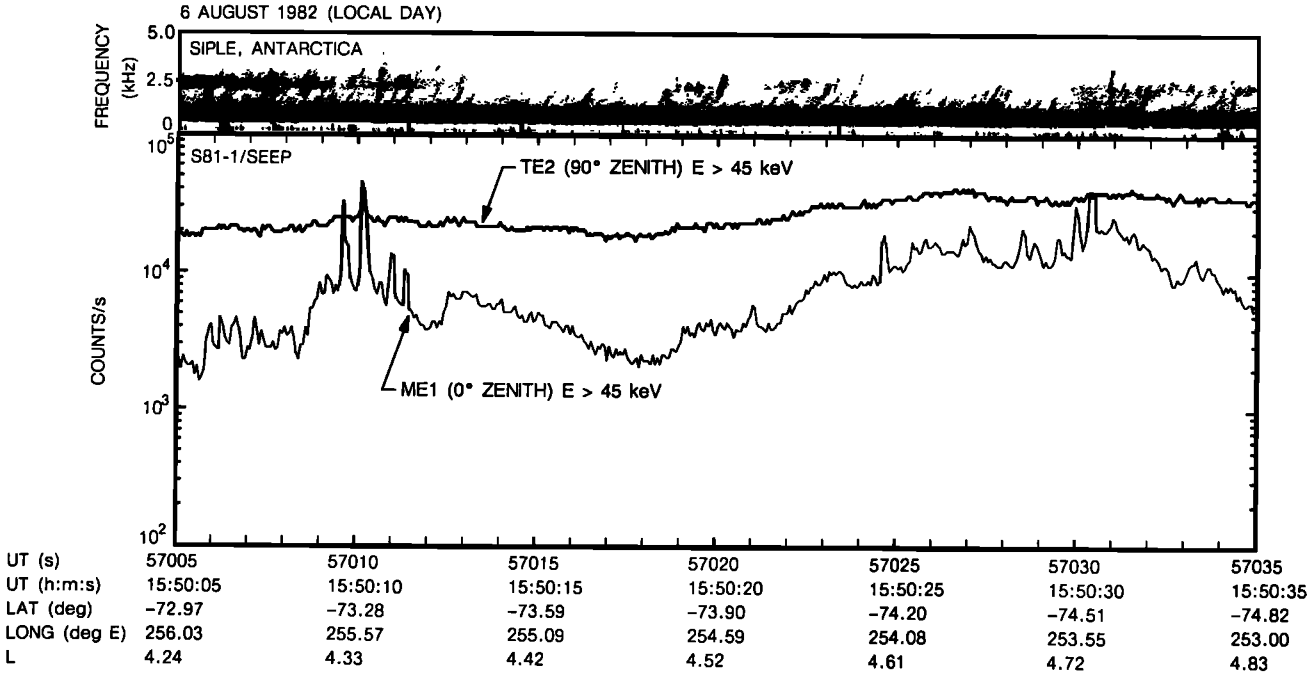

Fig. 14. In the upper section is shown the frequency-time record as recorded at Siple station. In the bottom section the counting rates in the ME1 (>45 keV) detector at 0° zenith angle and the TE2 (>45 keV) detector at 90° zenith angle are plotted as a function of time.

of the Siple longitude (and thus passed within ~220 km of the station). In 5 of these 9 cases, the number of short bursts detected between $L = 3$ and $L \simeq 5$ was relatively small (1, 3, 5, 5, 6), and in only one of these cases was overhead burst precipitation clearly indicated at Siple. However, in the remaining four cases, there were 10 or more narrow electron bursts recorded on the SEEP payload (10, 18, 24, 35), indicating a high temporal rate of activity. In all four of these cases, overhead perturbations of several seconds duration were clearly detected at Siple, as indicated by correlated changes in the 2 to 4 kHz integrated amplitude and one or more of the outputs of a riometer, photometer, and magnetometer. These precipitation episodes, lasting 1 to 3 hours, were detected either during the SEEP pass or within less than one hour before or after the pass. In all four cases, the activity had been recognized by the Siple Station observer.

Figure 15 shows portions of the Siple station analog chart used to monitor the outputs of multiple sensors. The record is from July 24, 1982, and represents an interval within 10 min of the nearly overhead SEEP pass illustrated in Figure 12. The charts indicate that this type of activity had been underway for at least 30 min prior to the SEEP pass and that it continued for at least 90 min afterward. Peak to peak correlations exist between many of the changes on the VLF and optical records, although the VLF surges are broader, probably due to contributions from magnetospheric wave paths outside the field of view of the vertical looking photometer.

DISCUSSION

Our study suggests that narrow (<1 s) burst activity is a global phenomenon, occurring at essentially all longitudes and at latitudes both within and beyond the plasmasphere. At $L = 2$ to 3 there appears to be some clustering of the

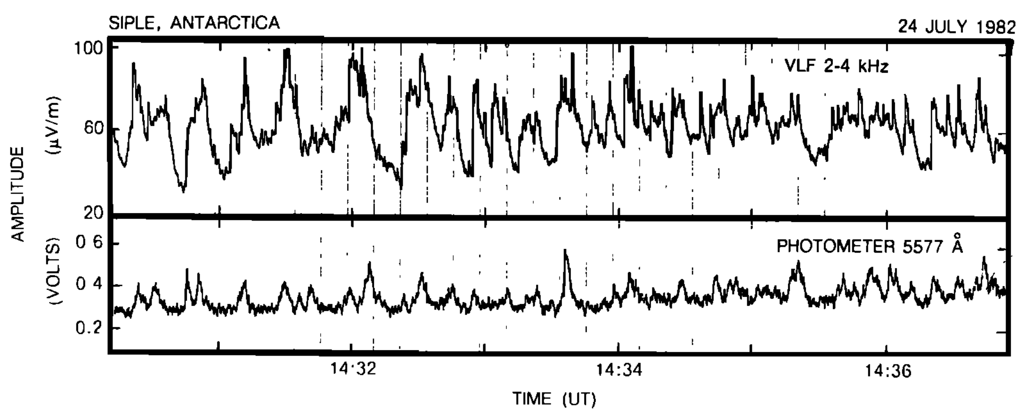

Fig. 15. Portions of the Siple Station analog chart for July 24, 1982, showing VLF amplitude in the 2 to 4 kHz band and the intensity of the 5577-Å line excited by precipitating electrons.

activity in local time, longitude, and hemisphere, due to the mixed effects of whistler source activity, day-night differences in ionospheric absorption of VLF waves, magnetic field topology, and instrument sensitivity. Our study further suggests that the bulk of the narrow bursts occurred as the result of interaction with transient VLF waves. This conclusion is supported by the electron observations themselves, which showed energy spectra and time and pitch angle signatures that were generally consistent with previous theoretical and experimental studies of particle scattering by VLF waves. The burst events at L = 2 to 3 were rare by comparison to the L = 3 to 5 activity, both in terms of the number of passes on which one or more events were detected and the occurrence of multiple events on a given pass. This feature is believed to be linked to the quasi-continuous nature and wide spatial distribution of chorus activity above $L = 3$, and to the concentration of this chorus activity outside the plasmapause, where trapped particle fluxes tend to be larger than those near the slot region. In comparison ducted whistlers tend to occur irregularly, at highly variable average rates and are most common on paths within the plasmasphere [*Carpenter and Sulic*, 1988].

The absence of one-to-one correlations between electron bursts and chorus elements and the presence of such correlations with whistlers can be partially understood as follows. In the case of a whistler the lightning source usually excites multiple ducted paths and also illuminates magnetospheric regions in which energy propagates in the nonducted mode. Because of the spatially distributed and both ducted and nonducted nature of this propagation, whistler components received at a ground station will mark the occurrence of a whistler, without in fact being that specific part of the whistler-mode energy involved in producing an observed particle event. On the other hand, in the case of chorus, there may be no mutual coherence between chorus elements originating spontaneously at various high altitude locations distributed in L value and longitude. Thus, if on ground records, a chorus element is to serve as a marker of a particular satellite-observed electron burst, the element must be a propagated component of the actual driving wave. Meanwhile, however, it will tend to be mixed with wave contributions from high altitude regions whose ionospheric projections are not being probed at that time by the satellite. However, if chorus bursts are whistler-triggered over a distributed region, a large measure of spatial coherence will be present and there should be increased probability of detecting correlations. This type of burst has been observed in several of the ground and balloon-based correlations reported to date [*Rosenberg et al.*, 1971; *Helliwell et al.*, 1980].

If the chorus elements associated with a series of electron bursts are nonducted, they are not likely to be observed on the ground at all because of wave absorption and reflection within the magnetosphere [*Kimura*, 1966; *Edgar*, 1976]. Nonducted chorus may have been a factor in both the $L > 3$ and $L < 3$ electron bursts observed on the dayside. At $L < 3$ nonducted chorus of the special type reported by *Poulsen and Inan* [1988] may have been involved as well as whistlers and ducted chorus events. The Poulsen and Inan chorus was found to occur at $2 < L < 4.5$, preferentially in the dawn sector under relatively disturbed conditions and within a frequency band whose limiting frequencies varied with satellite L value. On many satellite records it was the dominant natural wave activity in an L range spanning the plasmapause.

Several-second-long precipitation bursts were observed overhead Siple during (or within one hour of) all four of the nearby SEEP passes on which more than 10 bursts were observed. We suggest that the satellite was sampling the electron population associated with the ground-observed activity. The narrow ~0.3-s bursts observed on SEEP were possibly due to individual spontaneous or whistler-triggered chorus elements of particularly high amplitude, while the wider, order of 10-second surges on the satellite may have been caused by the integrated effects of chorus elements closely spaced in time. While these surges may be related to the ground observations of several-second-long bursts, the connection is not yet clear. Dayside cases were found in which broader electron bursts, not qualifying as narrow events, were observed in the L = 2 to 3 range as the satellite passed close to the meridian of Siple (276°E) and Palmer (296°). In these cases, strong VLF chorus was detected at Siple ($L \simeq 4.3$) and Palmer ($L \simeq 2.4$), but one-to-one correlations between the envelopes of the wave and electron burst activity could not be established.

It is of interest to review the similarities and differences between the mid- and high-latitude bursts. Perhaps the most pronounced difference is that at midlatitudes the narrow bursts were often isolated, whereas at high latitudes they frequently occurred in trains. The evidence suggests that the midlatitude events occurred within the plasmasphere, with some possible exceptions on the dayside. In contrast, the more numerous high-latitude events occurred poleward of the plasmapause. After the initial burst the midlatitude events often showed secondary pulses that can be attributed to the bouncing of an electron bunch between hemispheres. At mid-latitudes the narrow events occurred more often near midnight than noon, apparently because of the combined effects of greater nighttime lightning activity and lower nighttime wave absorption in the ionosphere. At high latitudes the daytime activity was greater, apparently because of the dayside concentration of magnetospheric chorus activity.

Only the nighttime bursts at mid-latitudes frequently displayed a pronounced increase in median energy with time, consistent with electron scattering by a whistler train. Peaks in the energy spectra often occurred at night, but were seldom present in the daytime. Chorus is believed to be associated with the high-latitude events both at noon and midnight, and with perhaps some of the midlatitude bursts near noon, whereas the nighttime events at mid latitudes are believed to be associated with whistlers.

Acknowledgments. The SEEP payload (ONR 804) on the S81-1 spacecraft was sponsored by the Office of Naval Research (contract N00014-79-C-0824). Orbital support was provided by the Air Force Space Test Program Office. Some of the data analysis was sponsored by the Office of Naval Research (contract N00014-88-C-0033). Additional data analysis was sponsored by the Lockheed Independent Research Program. Appreciation is extended to D. W. Datlowe and E. E. Gaines for their various roles in the SEEP experiment and to J. P. McGlennon for his effort in processing the data. We appreciate discussions with colleagues at Stanford, notably with R. A. Helliwell. We thank J. P. Katsufrakis for his contributions to the coordination of the Stanford portion of the SEEP experiments. We also thank J. Yarbrough for the processing of the wave data. The Stanford University effort for this work was supported by the Office of Naval Research under grant N00014-82-K-0489. Additional support was provided by the Division of Polar Programs of the National Science Foundation under DPP-86-13783. Appreciation is extended to S. B. Mende for use of data from a photometer at Siple station.

The Editor thanks J. R. Benbrook and another referee for their assistance in evaluating this paper.

REFERENCES

Arnoldy, R. L., K. Dragoon, L. J. Cahill, Jr., S. B. Mende, and T. J. Rosenberg, Detailed correlations of magnetic field and riometer observations at $L = 4.2$ with pulsating aurora, *J. Geophys. Res.*, *87*, 10,449, 1982.

Burtis, W. J., and R. A. Helliwell, Magnetospheric chorus: Occurrence patterns and normalized frequency, *Planet. Space Sci.*, *24*, 1007, 1976.

Burton, R. K., and R. E. Holzer, The origin and propagation of chorus in the outer magnetosphere, *J. Geophys. Res.*, *79*, 1014, 1974.

Cain, J. C., S. J. Hendricks, R. A. Langel, and W. V. Hudson, A proposed model for the international geomagnetic reference field, *J. Geomagn. Geoelectr.*, *19*, 335, 1967.

Carpenter, D. L., Whistler studies of the plasmapause in the magnetosphere, 1, Temporal variations in the position of the knee and some evidence on plasma motions near the knee, *J. Geophys. Res.*, *71*, 693, 1966.

Carpenter, D. L., and C. G. Park, On what ionospheric workers should know about the plasmapause-plasmasphere, *Rev. Geophys.*, *11*, 133, 1973.

Carpenter, D. L., and D. M. Sulic, Ducted whistler propagation outside the plasmapause, *J. Geophys. Res.*, *93*, 9731, 1988.

Carpenter, D. L., U. S. Inan, F. W. Pascual, and A. J. Smith, A new VLF method for studying burst precipitation near the plasmapause, *J. Geophys. Res.*, *90*, 4383, 1985.

Edgar B. C., The upper and lower frequency cutoffs of magnetospherically reflected whistlers, *J. Geophys. Res.*, *81*, 205, 1976.

Foster, J. C., and T. J. Rosenberg, Electron precipitation and VLF emissions associated with cyclotron resonance interactions near the plasmapause, *J. Geophys. Res.*, *81*, 2183, 1976.

Goldberg, R. A., S. A. Curtis, and J. R. Barcus, Detailed spectral structure of magnetospheric electron bursts precipitated by lightning, *J. Geophys. Res.*, *92*, 2505, 1987.

Hardy, D. A., and W. J. Burke, Observations of auroral electron precipitation produced by VLF waves (abstract), *Eos Trans. AGU*, *68*, 1440, 1987.

Helliwell, R. A., *Whistlers and Related Ionospheric Phenomena*, Stanford University Press, Stanford, Calif., 1965.

Helliwell, R. A., J. P. Katsufrakis, and M. L. Trimpi, Whistler-induced amplitude perturbation in VLF propagation, *J. Geophys. Res.*, *78*, 4679, 1973.

Helliwell, R. A., S. B. Mende, J. H. Doolittle, W. C. Armstrong, and D. L. Carpenter, Correlations between $\lambda 4278$ optical emissions and VLF wave events observed at $L \sim 4$ in the Antarctic, *J. Geophys. Res.*, *85*, 3376, 1980.

Hurren, P. J., A. J. Smith, D. L. Carpenter, and U. S. Inan, Burst precipitation-induced perturbations on multiple VLF propagation paths in Antarctica, *Ann. Geophys.*, *4*, 311, 1986.

Imhof, W. L., H. D. Voss, M. Walt, E. E. Gaines, J. Mobilia, D. W. Datlowe, and J. B. Reagan, Slot region electron precipitation by lightning, VLF chorus, and plasmaspheric hiss, *J. Geophys. Res.*, *91*, 8883, 1986.

Inan, U. S., and D. L. Carpenter, On the correlation of whistlers and associated subionospheric VLF/LF perturbations, *J. Geophys. Res.*, *91*, 3106, 1986.

Inan, U. S., and D. L. Carpenter, Lightning-induced electron precipitation events observed at $L = 2.4$ as phase and amplitude perturbations on subionospheric VLF signals, *J. Geophys. Res.*, *92*, 3293, 1987.

Inan, U. S., T. G. Wolf, and D. L. Carpenter, Geographic distribution of lightning-induced electron precipitation observed as VLF/LF perturbation events, *J. Geophys. Res.*, *93*, 9841, 1988.

Inan, U. S., M. Walt, H. D. Voss, and W. L. Imhof, Energy spectra and pitch angle distributions of lightning-induced electron precipitation: Analysis of an event observed on the S81-1 (SEEP) satellite, *J. Geophys. Res.*, *94*, 1379, 1989.

Kimura, I., Effects of ions on whistler mode ray tracing, *Radio Sci.*, *1*, 269, 1966.

McNerney, P. C., U. S. Inan, W. L. Imhof, H. D. Voss, and M. Walt, A satellite-ground study of lightning induced electron precipitation events and their association with whistlers and VLF perturbations (abstract), *Eos Trans. AGU*, *68*, 1222, 1987.

Mobilia, J., H. D. Voss, and W. L. Imhof, Lightning observations from the SEEP/S81-1 satellite (abstract), *Eos Trans. AGU*, *66*, 1001, 1985.

Oliven, M. N., and D. A. Gurnett, Microburst phenomena, 3, An association between microbursts and VLF chorus, *J. Geophys. Res.*, *73*, 2355, 1968.

Orville, R. E., and R. W. Henderson, Global distributions of midnight lightning: September 1977 to August 1978, *Mon. Weather Rev.*, *114*, 2640, 1986.

Poulsen, W. L., and U. S. Inan, Satellite observations of a new type of discrete VLF emission at $L < 4$, *J. Geophys. Res.*, *93*, 1817, 1988.

Rosenberg, T. J., R. A. Helliwell, and J. P. Katsufrakis, Electron precipitation associated with discrete very low-frequency emissions. *J. Geophys. Res.*, *76*, 8445, 1971.

Rosenberg, T. J., J. C. Siren, D. L. Matthews, K. Marthinsen, J. A. Holtet, A. Egeland, D. L. Carpenter, and R. A. Helliwell, Conjugacy of electron microbursts and VLF chorus, *J. Geophys. Res.*, *86*, 5819, 1981.

Rycroft, M. J., Enhanced energetic electron intensities at 100 km altitude and a whistler propagating through the plasmasphere, *Planet. Space Sci.*, *21*, 239, 1973.

Tsuruda, K., S. Machida, T. Oguti, S. Kobubun, K. Hayashi, T. Kitamura, O. Saka, and T. Watanabe, Correlations between the very low frequency chorus and pulsating aurora observed by low-light-level television at $L \simeq 4.4$, *Can. J. Phys.*, *59*, 1042, 1981.

Turman, B. N., and B. C. Edgar, Global lightning distributions at dawn and dusk, *J. Geophys. Res.*, *87*, 1191, 1982.

Voss, H. D., J. B. Reagan, W. L. Imhof, D. O. Murray, D. A. Simpson, D. P. Cauffman, and J. C. Bakke, Low temperature characteristics of solid state detectors for energetic X-ray, ion and electron spectrometers, *IEEE Trans. Nucl. Sci.*, *NS-29*, 164, 1982.

Voss, H. D., W. L. Imhof, M. Walt, J. Mobilia, E. E. Gaines, J. B. Reagan, U. S. Inan, R. A. Helliwell, D. L. Carpenter, J. P. Katsufrakis, and H. C. Chang, Lightning-induced electron precipitation, *Nature*, *312*, 740, 1984.

D. L. Carpenter and U. S. Inan, STAR Laboratory, Stanford University, Stanford, CA 94305.

W. L. Imhof, J. Mobilia, H. D. Voss, and M. Walt, Lockheed Missiles and Space Laboratory, Dept. 91-20, Bldg. 255, 3251 Hanover St., Palo Alto, CA 94304.

(Received January 23, 1989;
revised March 27, 1989;
accepted April 5, 1989.)