LMSC/F247028 ②

PROGRESS REPORT

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Contract N00014-88-C-0033

MECHANISMS FOR THE SOURCE AND LOSS OF ELECTRONS

Space Sciences Laboratory
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PROGRESS REPORT

SUMMARY

The objectives of this contract are to use available satellite particle and bremsstrahlung x-ray data as well as ground based measurements to evaluate the source and loss mechanisms for electrons trapped throughout the radiation belts. Much of ~~our current~~ effort has concentrated on compiling the existing electron precipitation data over a wide range of latitudes and comparing the electron data with available wave data. At midlatitudes extensive effort has been devoted to comparing the short duration bursts observed in the SEEP payload on the S81-1 satellite with narrow bursts in the wave data recorded, by the Stanford group at Siple and Palmer ground stations. In several daytime cases general agreement was obtained between chorus wave emissions and electron precipitation bursts, but one-to-one coincidences were not observed. The association of electron precipitation at nighttime with lightning generated whistlers is much better in several recently uncovered examples as well as earlier ones.

A major contribution to the total electron precipitation rate is associated with those injected into the drift loss cone. Much of the flux observed in the drift loss cone is associated with the nearly monochromatic waves emitted from VLF transmitters, as indicated by narrow peaks in the energy spectra. Recently, we have been studying the fluxes and energy spectra of electrons observed at nighttime in the eastern hemisphere. A concentration of the electrons occurs primarily in the vicinity of Northwest Cape, Australia (NWC).

Our study of electron precipitation at high latitudes has benefited from use of bremsstrahlung x-ray data acquired on the SEEP payload as well as the P78-1 satellite.

The x-ray spectrometers on P78-1 have been very useful for studying the electron precipitation that regularly occurs near the trapping boundary. For the first time we have found that the precipitation pattern often extends over a large longitude interval, as much as 60°. We have also found the precipitation to be reasonably steady for times as long as 5 minutes. This investigation has provided support for the hypothesis that the precipitation is associated with irregularities in the magnetic field lines near the trapping boundary. Earlier in this program we studied the various precipitation patterns at high latitudes, including small isolated patches, and the results were published earlier this year in two papers (abstracts are included in the Appendix).

I. ELECTRON PRECIPITATION IN BURSTS

Satellite observations of short duration (<0.6s) electron (E>6 keV) precipitation bursts, detected by the spectrometers on the low altitude polar orbiter S81-1, have been correlated with simultaneous ground-based VLF wave measurements from Palmer (L = 2.4) and Siple (L = 4.2) stations in Antarctica. Comparisons were made between the characteristics of the electron events at night (2230) and in the daytime (1030), at midlatitudes (L = 2 to 3) and at high latitudes (L > 3). For 2 < L < 3 the daytime electron precipitation bursts occurred approximately uniformly in longitude and were equally distributed between the northern and southern hemispheres. These distributions contrast with those of nighttime bursts in the same L-shell range which 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. For most short daytime bursts at L = 2 to 3 the energy spectra did not show a consistent, well-defined temporal trend, whereas in a significant number of the nighttime events the electron energies increased with time. 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. The wave frequencies for wave-particle interactions were calculated from the measured electron energies and were consistent with chorus or whistler emissions. Several of the nighttime electron bursts at L = 2 to 3 were correlated with whistler emissions, as illustrated in Figure 1. For only one midlatitude electron burst in the daytime, which was recorded when coordinated wave data were also acquired, chorus activity was present, as shown in Figure 2. These findings are summarized in a paper by Imhof, Voss, Mobilia, Walt, Inan, and Carpenter which is nearly ready for submission to the Journal of Geophysical Research.

Detailed studies have and are being made of electron precipitation induced by lightning. The results of the joint investigations by the Lockheed and Stanford groups are summarized in a recent paper by Inan, Voss, Walt, and Imhof. The abstract of this paper is included in Appendix A. More analyses are being performed by the same groups and will appear in a paper by Voss et al. Further results of the lightning studies are scheduled to be presented by Voss at the 1988 fall meeting of the American Geophysical Union and by Voss et al. and by Mobilia et al. at the January 1989 meeting of the American Association for the Advancement of Science.

II. ELECTRON PRECIPITATION AT MIDLATITUDES INTO THE DRIFT LOSS CONE

A comprehensive study of the narrow L-dependent spectral peaks in the S81-1 /SEEP electron data was carried out. The peaks can be identified by their characteristic outline on color plots of electron flux versus energy and time. Spectrograms were produced for all of the time intervals containing narrow resonance peaks; the prints were marked at the time of each visible event with notations indexing the peak into a master catalog of events. The master catalog, containing 680 events, gives the time of observation, location, and other information about the events; this catalog is the basis for the map of peak location, shown in Figure 3.

To study these events in detail, pulse height data with high time resolution are required; these can be obtained only from the original raw data tapes. For about 200 of the most interesting events, TE2 spectral data from 6 keV to 1 MeV were extracted from the raw data and stored on disk files. These files are the basis of contour plots of flux versus energy and L-value. These plots follow the characteristic curve expected for resonance at the geomagnetic equator with waves at frequency of about 20 kHz. Plots of this type were scanned for the range of L-values over which they are observed and for the flux at the most intense point; these values were added to the database.

The occurrence of the peaks in the eastern hemisphere is strongly clustered around the longitude of the station NWC and to the east of it, as shown in Figure 4. In addition, the strongest peaks are very close to 114°E, the location of NWC. These occurrence data suggest very strongly that the transmitter at NWC is the source of the waves which are precipitating these electrons. The contour plots of flux vs L and energy are entirely consistent with the 22.3 kHz frequency of this station, although several assumptions are required to make this plot. Work in progress includes a search for peaks to the west of NWC, upstream from the direction of electron drift in the magnetosphere. At present there are only 7 events in this set, and they are found at a higher range of L-values, near $L = 1.9$.

III. ELECTRON PRECIPITATION AT HIGH LATITUDES

Electron precipitation at high latitudes is being studied with bremsstrahlung x-ray detectors on the S81-1 (SEEP) and the P78-1 satellites. Precipitation in small isolated patches was investigated with SEEP x-ray data and an abstract of a recent paper on this subject is included in the Appendix. Spectral maps of electron precipitation in arcs near midnight at high latitudes have been studied with SEEP x-ray data and an abstract of a paper on this subject is also included in the Appendix.

Much of the electron precipitation at high latitudes commonly occurs along the outer edge of the radiation belt; i.e. near the trapping boundary. However, when the fluxes and energy spectra of the precipitating electrons are measured with an electron spectrometer they are obtained only along the narrow track of the satellite even though it is important to map these quantities at a given time along much of the trapping boundary. Examples of the variety of precipitation patterns that have been measured with electron spectrometers on different satellite passes are shown in Figure 5. Remote mapping of the precipitation patterns that occur simultaneously over a large area can most appropriately be done with the bremsstrahlung x-ray technique. Accordingly, we are beginning to analyze some bremsstrahlung x-ray data acquired at the trapping boundary. For this project we are very interested in the temporal and spatial variations as evidence for other sources of electron precipitation.

FIGURE CAPTIONS

Figure 1. In the top sections are shown the frequency-time record and the integrated wave intensity as recorded at Palmer Station. In the bottom section the counting rates in the ME1 (> 45 keV) detector at 0° and the TE2 (> 45 keV) detector at 90° are plotted as a function of time.

Figure 2. 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. Waves were recorded only for a period of 2 seconds out of each 5 seconds.

Figure 3. The longitude-latitude locations of the peaks observed in the energy spectra of electrons in the drift loss cone.

Figure 4. The number of events with L-dependent peaks in the energy spectra per degree of longitude versus the longitude of observation in degrees east.

Figure 5. Fluxes of trapped and precipitating electrons measured as a function of time and L shell on several passes of the P78-1 satellite.

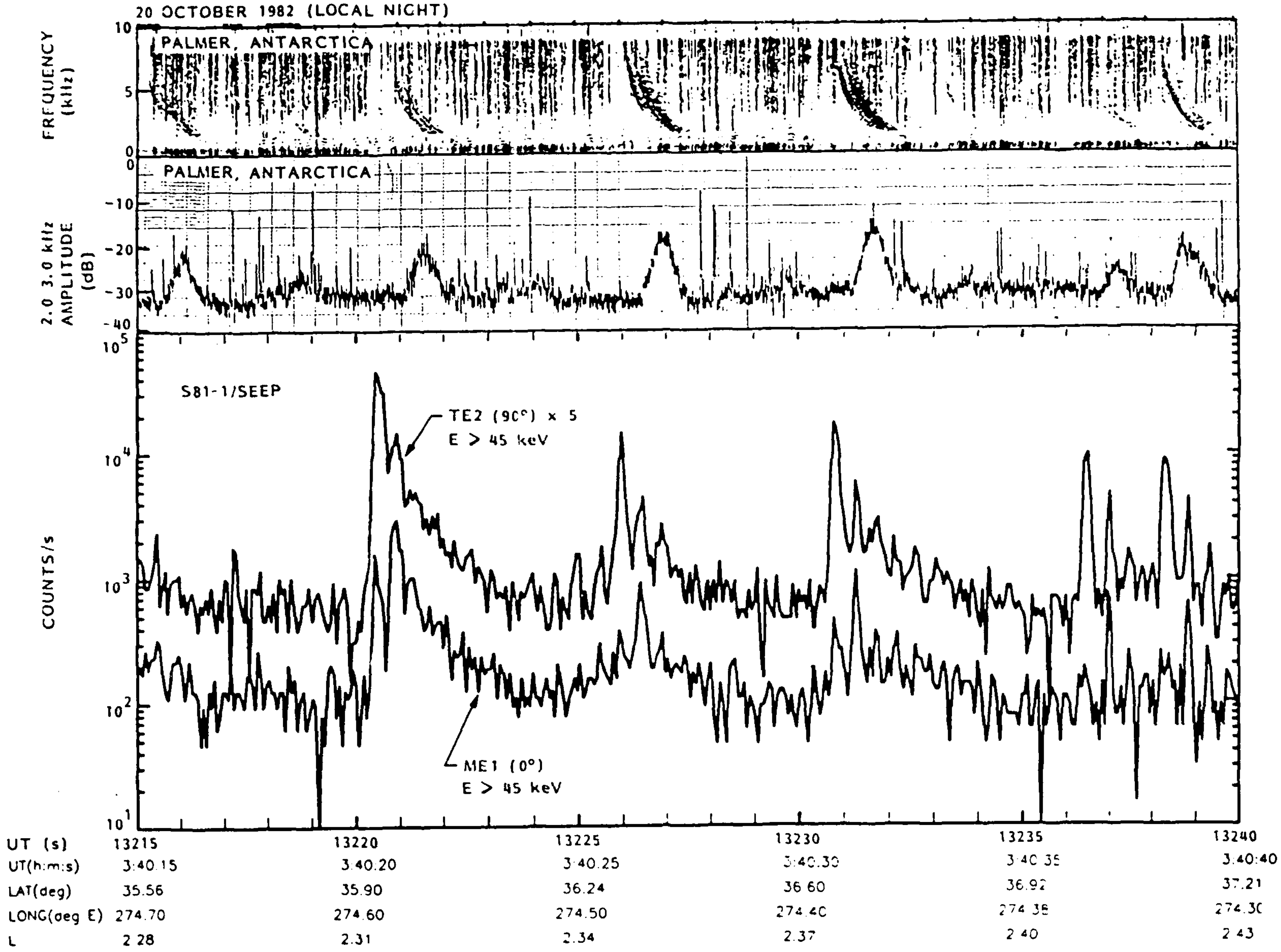

20 OCTOBER 1982 (LOCAL NIGHT)
PALMER, ANTARCTICA
FREQUENCY (kHz)
10
5
0
PALMER, ANTARCTICA
2.0 3.0 kHz AMPLITUDE (dB)
0
-10
-20
-30
-40
S81-1/SEEP
TE2 (90°) x 5
E > 45 keV
ME1 (0°)
E > 45 keV
COUNTS/s
10^5
10^4
10^3
10^2
10^1
UT (s) 13215 13220 13225 13230 13235 13240
UT(h:m:s) 3:40.15 3:40.20 3:40.25 3:40.30 3:40.35 3:40:40
LAT(deg) 35.56 35.90 36.24 36.60 36.92 37.21
LONG(deg E) 274.70 274.60 274.50 274.40 274.35 274.30
L 2.28 2.31 2.34 2.37 2.40 2.43

Figure 1

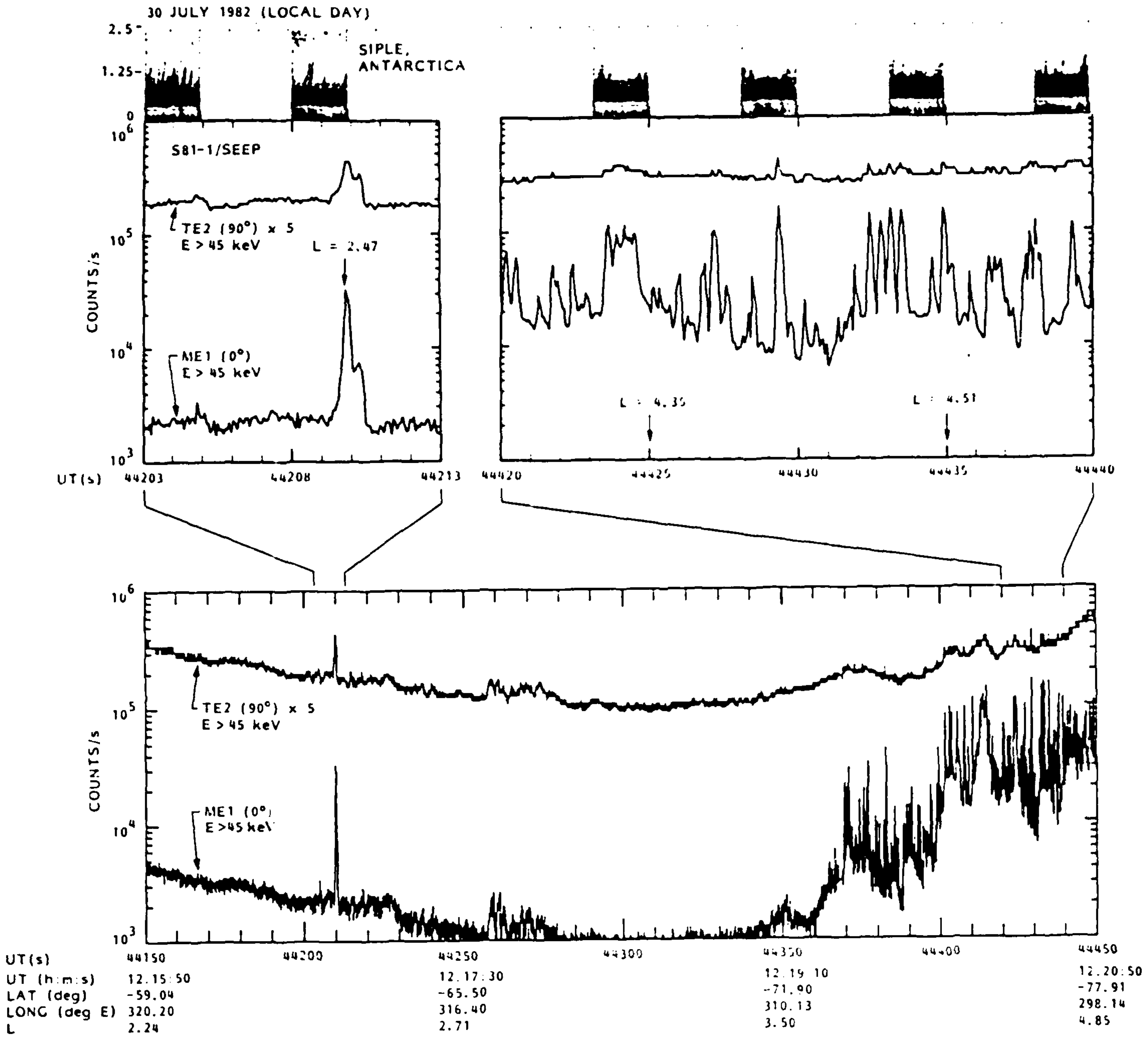

30 JULY 1982 (LOCAL DAY)
2.5
1.25
0
SIPLE, ANTARCTICA
S81-1/SEEP
10^6
10^5
10^4
10^3
COUNTS/s
TE2 (90°) x 5
E > 45 keV
ME1 (0°)
E > 45 keV
L = 2.47
L = 4.35
L = 4.51
UT(s)
44203
44208
44213
44420
44425
44430
44435
44440
44150
44200
44250
44300
44350
44400
44450
UT (h:m:s)
LAT (deg)
LONG (deg E)
L
12.15:50
-59.04
320.20
2.24
12.17:30
-65.50
316.40
2.71
12.19:10
-71.90
310.13
3.50
12.20:50
-77.91
298.14
4.85

Figure 2

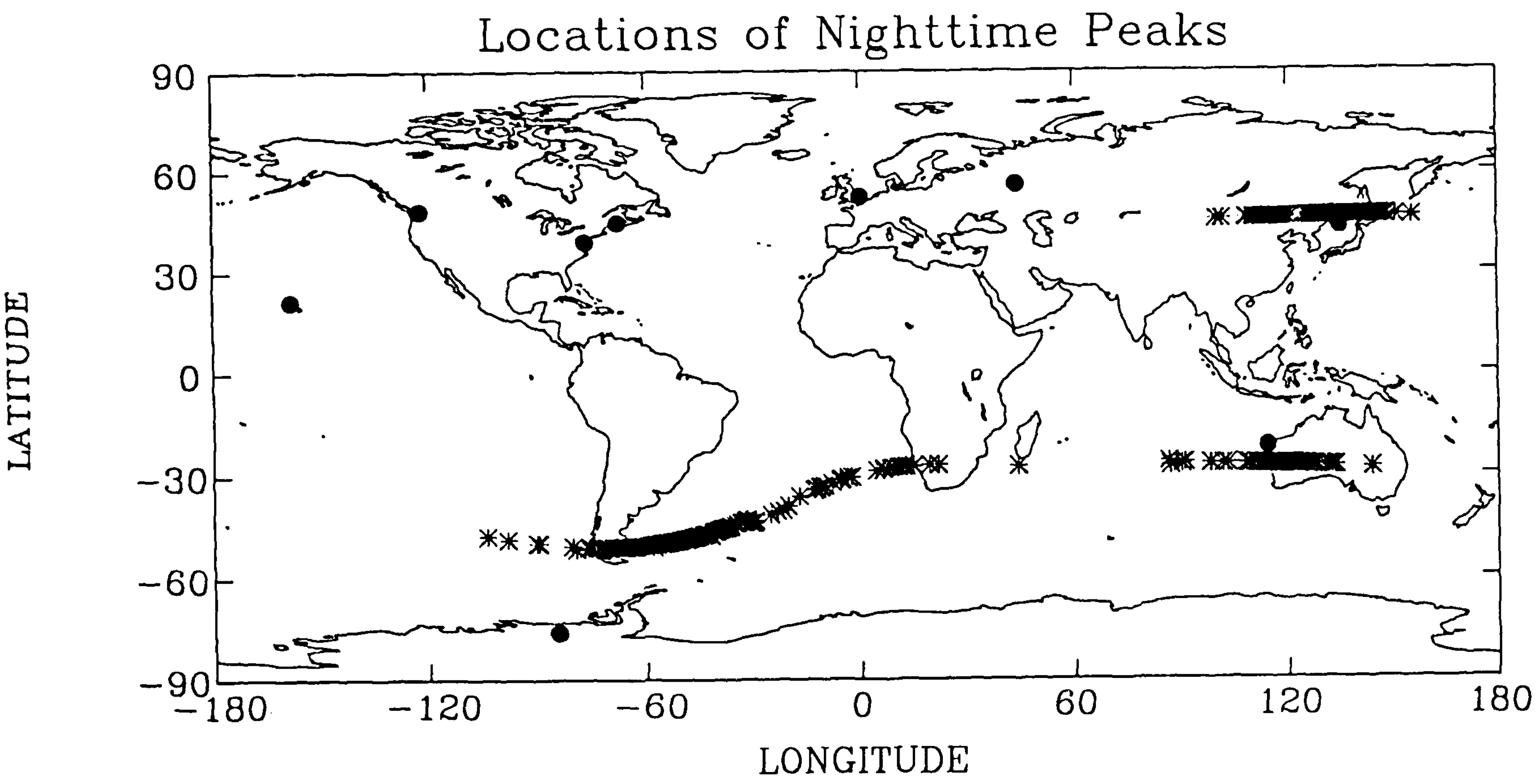

Locations of Nighttime Peaks
LATITUDE
90
60
30
0
−30
−60
−90
LONGITUDE
−180
−120
−60
0
60
120
180

Figure 3

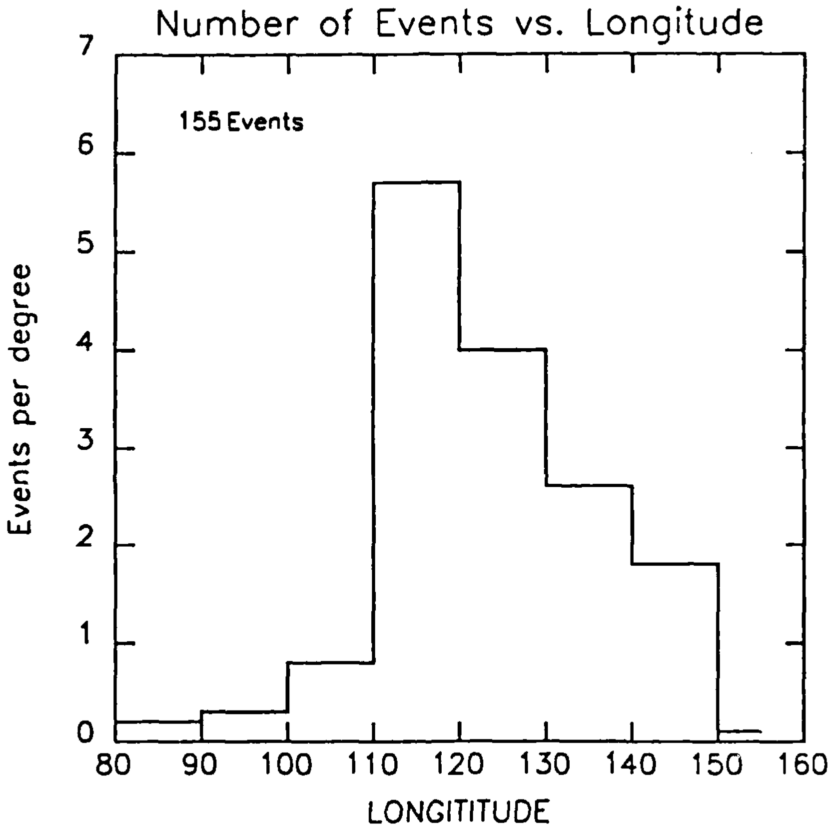
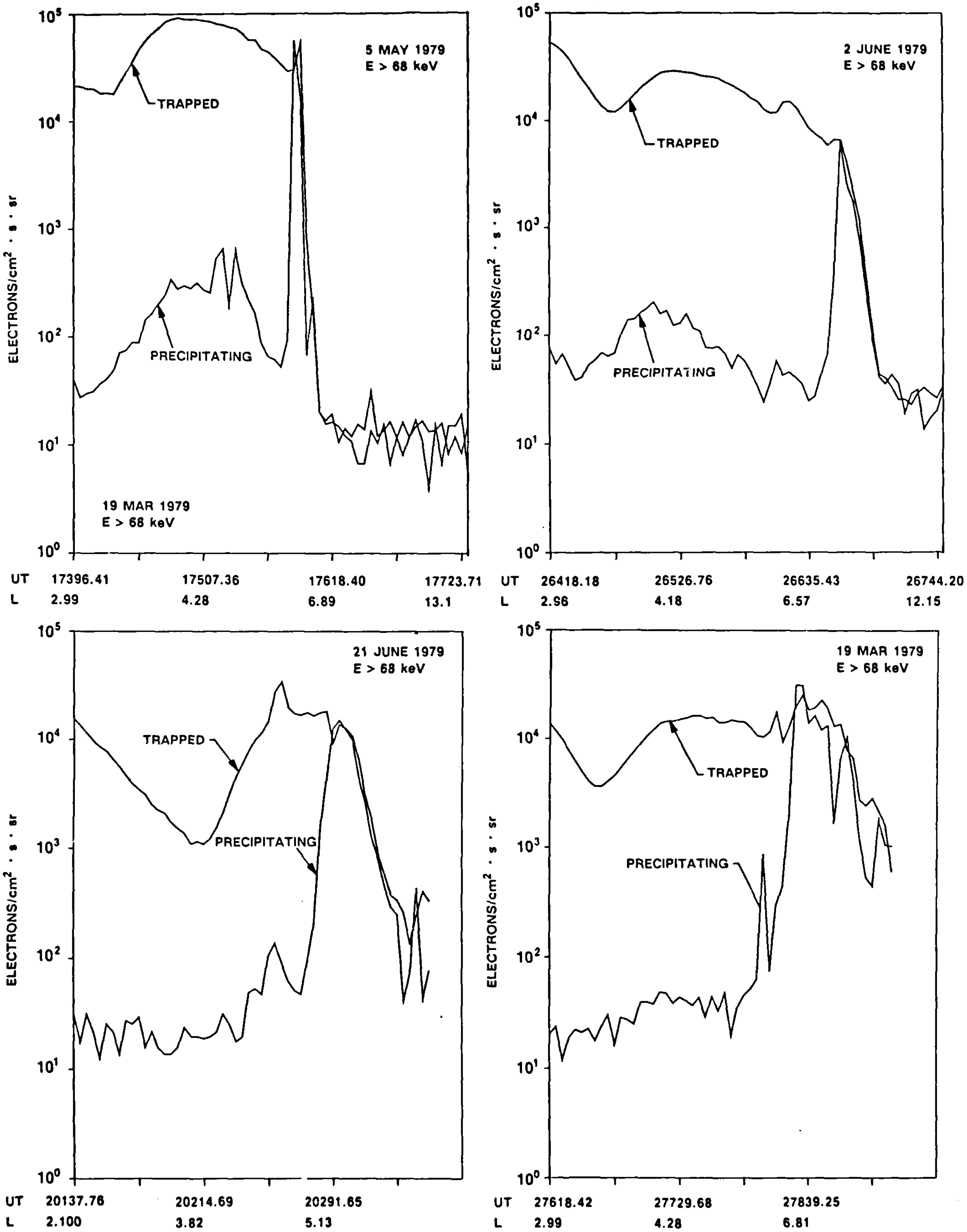

Number of Events vs. Longitude
155 Events
Events per degree
0
1
2
3
4
5
6
7
80
90
100
110
120
130
140
150
160
LONGITITUDE

Figure 4



10⁵
10⁴
10³
10²
10¹
10⁰
ELECTRONS/cm² · s · sr
5 MAY 1979
E > 68 keV
TRAPPED
PRECIPITATING
19 MAR 1979
E > 68 keV
UT 17396.41 17507.36 17618.40 17723.71
L 2.99 4.28 6.89 13.1
2 JUNE 1979
E > 68 keV
TRAPPED
PRECIPITATING
UT 26418.18 26526.76 26635.43 26744.20
L 2.96 4.18 6.57 12.15
21 JUNE 1979
E > 68 keV
TRAPPED
PRECIPITATING
UT 20137.76 20214.69 20291.65
L 2.100 3.82 5.13
19 MAR 1979
E > 68 keV
TRAPPED
PRECIPITATING
UT 27618.42 27729.68 27839.25
L 2.99 4.28 6.81

Figure 5

Accepted for Publication in JGR

Energy Spectra and Pitch Angle Distributions of Lightning-Induced Electron Precipitation: Analysis of an Event Observed on the S81-1(SEEP) Satellite

U. S. Inan

STAR Laboratory, Stanford University, Stanford, CA 94305

M. Walt, H. D. Voss, W. L. Imhof

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Submitted to *Journal of Geophysical Research*

July 1988

Temporal and spectral signatures of a Lightning-induced Electron Precipitation (LEP) burst observed on the S81-1(SEEP) satellite are analyzed and compared with the predictions of a test particle model of the gyroresonant whistler-particle interaction in the magnetosphere. The flux to be detected by specific detectors on the low altitude (~ 220 km) satellite at $L \simeq 2.24$ is calculated in terms of the integral counting rate as a function of time and in terms of the dynamic energy spectra during the initial ~ 300 ms precipitation pulse. For a whistler wave packet with frequency range 500 Hz to 6 kHz the dynamic energy spectra are found to depend sensitively on the electron angular distribution in the vicinity of the loss cone. In the case of a whistler wave originating in northern hemisphere lightning the maximum whistler-induced pitch angle scattering of electrons occurs near ~ 10°S geomagnetic latitude. However, scattering occurring over the latitude range of ~ 20°N to ~ 20°S is found to be significant and contributes to the observed LEP pulse. The dynamic energy spectra of the LEP pulse and the temporal profile of the integral counting rate are consistent with the predictions of a test particle model of the gyroresonant scattering of the electrons by a whistler wave having an equatorial intensity at 6 kHz of ~200 pT. The measured LEP pulse pitch angle distribution is wider than that estimated on the basis of the test particle model.

To Be Presented at Fall Meeting of AGU in S. F.

The Longitude Extent and the Temporal Stability of the Isotropic Electron Precipitation at the Nighttime Trapping Boundary

W. L. IMHOF, J. MOBILIA, D. W. DATLOWE, H. D. VOSS, and E. E. GAINES (Lockheed Palo Alto Research Laboratory, 3251 Hanover St., Palo Alto, CA 94304)

Temporal variations have previously been observed in electron precipitation near the outer edge of the radiation belts. Now for the first time a search has been conducted for the existence of such fluctuations associated solely with an isotropic trapping boundary and a study has been made of the longitude extent of the precipitation. Energetic electron precipitation from the radiation belts at the nightside trapping boundary has been mapped in both space and time using a combination of remote sensing bremsstrahlung x-ray (> 21 keV) and direct electron (> 68 keV) measurements from the low altitude polar orbiting satellite P78-1. The imaging capability of the x-ray instrument was used to observe the distribution in longitude and the time history of the precipitation over an extended area. Spacecraft passes were selected for study if the direct electron measurements indicated isotropy at the trapping boundary with no comparable precipitation at other latitudes. In these cases the electron precipitation was often found to extend over longitude intervals as wide as 40 degrees. On many of the selected satellite passes the precipitation was steady in time with no evidence for temporal variations of 10 to 100 seconds.

1. 1988 Fall Meeting

2. 001429913

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4. Magnetospheric Physics
(SM)

5. (a) No special session
(b) 2716 (Energetic
Particles,
Precipitating)

6. Oral

7. 0%

8. Invoice 40.00
Purchase Order ZAP-
202970X
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9. Contributed

To Be Presented at Fall Meeting of AGU in S. F.

Cyclotron Resonance Precipitation of Energetic Electrons from the Inner Magnetosphere

D W DATLOWE and W L IMHOF (Lockheed Palo Alto Research Laboratory, Palo Alto, California 94304)

Cyclotron resonance between trapped energetic electrons and VLF waves produces pitch angle scattering which leads to electron precipitation in the inner magnetosphere. Previous experiments have shown that in the drift loss cone at L values from 1.5 to 1.8 the energy spectrum of the electrons above 50 keV is often dominated by a single narrow peak. The center energy of this peak varies with L in a manner characteristic of scattering by monochromatic VLF waves interacting in the vicinity of the geomagnetic equator, and the source of the waves is probably VLF communication or navigation transmitters. We report here for the first time the results of a study of 680 occurrences of these peaks detected by the low altitude polar orbiting satellite S81-1. The present data, from altitudes between 170 and 270 km, show the resonance peaks only in two restricted longitude zones centered at 110°E and 300°E; this result contrasts with the previous measurements at higher altitudes, which detected peaks over a wide range of longitudes. Detailed study of the events occurring near 110°E reveals a 27 day periodicity in the frequency of occurrence; peaks are most often observed during minima in solar/geomagnetic activity. The peaks are observed only at nighttime and have a possible seasonal variation, being more frequent from May to September. Since it is widely recognized that the transmission of VLF waves up through the ionosphere is best at night, if the seasonal varation is related to the number of hours of nighttime at the source, then the seasonal variation suggests that the transmitter which is precipitating these electrons is located in the southern hemisphere.

1. 1988 Fall Meeting
2. 001380622
3. D. W. DATLOWE
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4. (SM) Magnetospheric Physics
5. No special session
   2716 (precipitating particles)
6. Oral
7. None
8. Invoice 40.00
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   Technical Information Center
   Lockheed Palo Alto Research
   Laboratory
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   3251 Hanover St.
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   Attention: Judy Conahan
9. Contributed

To Be Presented at Fall Meeting of AGU in S. F.

Lightning with Associated LEP and Electric Fields Observed from the SEEP/S81-1 Satellite

H. D. VOSS, (Lockheed Palo Alto Research Laboratory, 3251 Hanover St., Palo Alto, CA 94304)

During the period from May to December 1982 over 500 strong terrestrial lightning storms were observed with the cooled airglow photometer on board the low altitude and 3-axis stabilized SEEP/S81-1 satellite. The geographic distribution of the lightning flash events is found to be consistent with the location of major thunderstorm centers. In the vicinity of these lightning events and in L shell above 1.8, strong lightning-induced electron precipitating (LEP) bursts are frequently observed with the SEEP high-sensitivity solid state spectrometer array. The energy-time structure of the first pulse in several LEP events was recorded every 4 ms with a 256 channel analyzer and show an increase of electron energy from 100 to 300 keV in 300 ms near L = 2.2 at the edge of the loss cone. The increase of electron energy with time and the time delay after a lightning flash follows the cyclotron resonant frequency and the time delay of a 1/2 hop whistler near the geomagnetic equator. Subsequent electron pulses in the LEP event have a period of ~ 0.3 s (at L = 2.2) with a nearly isotropic distribution and are interpreted as bunches of magnetically guided 100 - 300 keV electrons which are repeatedly scattered from the conjugate atmosphere. Strong electric field coupling and plasma irregularities are furthermore suggested between tropospheric lightning flashes and the space environment based on current transients in the SEEP fixed-voltage plasma probe. The transient electric field signatures have rise-times shorter than the instrument resolution of 64 ms and recovery times of the order of 1 s at 230 km. The observed strength of the lightning-induced electric field transients may be sufficient to form plasma density irregularities and drive ionospheric currents.

1. 1988 Fall Meeting

2. 001387177

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4. Solar-Planetary
   Relationship and
   Atmospheric Science

5. (a)Special session on
   Lightning and Upper
   Atmospheric Effects
   (Whistlers)

6. Oral

7. 30%

8. Invoice 40.00
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9. Invited

To Be Presented at January 1989 Meeting of AAAS

Physical Sciences & Technology: Atmospheric Science
Solar-terrestrial, weather, coupling

Thunderstorm Effects in Space Observed with the SEEP S81-1 Satellite

H. D. VOSS, J. MOBILIA, and W. L. IMHOF (Lockheed Palo alto Research Laboratory, Palo Alto, Ca. 94304)

Strong coupling is suggested between the terrestrial and space environment based on the low-altitude SEEP/S81-1 satellite data. The SEEP observations above thunderstorms include: remote sensing of 391.4 and 630.0 nm wavelengths from lightning flashes, in situ measurements near 200 km altitude of medium scale travelling ionospheric disturbances (TIDs), lightning-induced electron precipitation (LEPs) and electric field transients. Thunderstorm weather fronts have been identified from weather satellite maps as being located in the 391.4 nm flash regions and directly beneath the in situ SEEP measurements of TIDs, electric field spikes, and LEP bursts. The TIDs have a horizontal wavelength of about 200 km and may be the result of a gravity wave produced from the thunderstorm activity. The transient electric field signatures have rise times faster than the instrument resolution of .064 sec. The energetic electron precipitation bursts ($50 < E < 500$ keV) have energy fluences as great as 10^{-3} ergs cm^{-2} and were frequently observed in the radiation belt slot region between L-shells of 2 and 3.

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To Be Presented at January 1989 Meeting of AAAS

Physical Science and Technology: Physics
lightning, atmosphere, ionosphere

Global Lightning Observations and Associated Effects as Measured from the S81-1/SEEP Satellite.

J. MOBILIA, H. D. VOSS, and W. L. IMHOF (Lockheed Palo Alto Research Laboratory, Palo Alto, California 94304)

During the period from May to December 1982 over 1000 strong terrestrial lightning events were remotely sensed with the cooled quadrant photometer on-board the low altitude (~200 km) and 3-axis stabilized S81-1/SEEP satellite. The SEEP payload (ONR 804) consisted of a quadrant photometer, an array of cooled solid-state particle spectrometers, a plasma probe, and an X ray detector. The SEEP photometer monitored the molecular nitrogen excitation line (391.4 nm) with two narrow bandwidth filters ($\Delta\lambda$ = 0.8 and 2.4 nm) and an atomic oxygen line (630.0 nm, $\Delta\lambda$ = 1.6 nm). These are known from groundbased studies to be components of the lightning spectrum. The geographic distribution of lightning flash events is found to be consistent with the location of the major thunderstorm centers. This global distribution was acquired at a local time ~10:30 in the evening. VLF waves generated from a lightning burst will interact with electrons in the Van Allen radiation belts causing some of the electrons in the belts to precipitated into the atmosphere. These Lightning-induced Electron Precipitation (LEP) events were measured in situ with the SEEP particle spectrometers during some of the observed lightning flashes. The observed lightning flashes were also accompanied on occasion by electric field transients as measured by the on-board plasma probe.

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Isolated Electron Precipitation Regions at High Latitudes

W. L. IMHOF, H. D. VOSS, D. W. DATLOWE, AND J. MOBILIA

Lockheed Palo Alto Research Laboratory, Palo Alto, California

An investigation has been made at high latitudes of regions or patches of isolated electron precipitation with bremsstrahlung X ray images (>4 keV) and simultaneous particle and 391.4-nm data acquired with the Stimulated Emission of Energetic Particles payload on the S81-1 satellite. More extensive analyses of the phenomena than were originally reported (Imhof et al., 1985) have now been made. From this investigation it has been found that when some patch regions are processed with greater sensitivity, nearby weaker patches are found. This characteristic suggests that some of them may be parts of larger structures. There is considerable overlap in spectral shape between patches and larger structures, but the energy spactra of the X rays emitted from the patches are, on the average, softer, even at similar invariant latitudes. Although some patches may be associated with auroral substorms as indicated from comparisons with the *AE* index, the majority are not and therefore appear not be related to westward traveling surges. Most patches are significantly narrower in one direction, consistent with arc-shaped precipitation. Fine structure is present in some patches, and study of the bremsstrahlung X ray measurements indicates that on a statistical basis many of the spikes associated with the fine structure are spatial and not temporal in nature, suggesting multiple arcs. Also consistent with arc structure, the local time variations have been found to display a similarity to those associated with inverted-V events, but the measured electrons are at higher energies than are normally associated with such events. In summary, at least some of the small precipitation patches reported here seem to be parts of larger structures which may encompass a variety of forms, including those that are arc-shaped in nature.

INTRODUCTION

Bremsstrahlung X ray images associated with isolated regions or patches of electron precipitation at high latitudes were recently discovered [*Imhof et al.*, 1985] with a fine-resolution X ray imager. These patches with widths of 100–300 km were found to occur very infrequently (29 out of 1022 satellite passes). The source(s) of the patches is (are) still not understood. In order to gain a better knowledge of the responsible mechanisms the following matters should be investigated:

1. A study should be made of any measurable secondary patches associated with strong identifiable regions of the type previously studied. The presence of weaker patches nearby would suggest that the patches may be parts of larger structures. Comparisons of the spectral characteristics among patches may indicate whether the patches appear to have a common origin and what that might be.

2. How do the X ray energy spectra of the patches compare with those of larger structures such as auroral arcs?

3. It is of interest to search for possible correlations between the occurrences of bremsstrahlung X ray patches and various indicators of geomagnetic conditions such as the *AE* index and the direction of the interplanetary magnetic field.

4. A search should be made for fine structure within a patch. An examination should be made of the fine time and spatial structure observed with particle spectrometers in association with the X ray patches. As we shall see, finer spatial structure (8–24 km in distance) than can be resolved in the X ray data is sometimes observed in direct electron measurements. The latter measurements leave open the ambiguity of spatial versus temporal variations, but the associated X ray measurements in which a particular area is viewed for a period of time may resolve this matter. The data acquired with electron spectrometers can provide fine-scale measurements with high precision of the intensities and spectral shapes. With a combination of electron and X ray measurements one can therefore investigate how often fine structure occurs, and when it does, detailed information can be obtained.

5. The local time distribution may be a signature which helps to identify the source of the patches. In the original paper on this subject [*Imhof et al.*, 1985] it was found that the majority of X ray patches occurred from dusk until dawn, but a few were present in the early afternoon hours. This local time distribution should be compared with that known for other features such as inverted-V events.

6. The presence of electric fields around the X ray regions considered here is a subject which should be investigated. Electric fields are known to be associated with polar cap discrete arcs [*Burch et al.*, 1979] and with inverted-V events [*Gurnett and Frank*, 1973]: discrete arcs, inverted-V events, and auroral arcs being somewhat synonymous but frequently having different meanings [*Heelis et al.*, 1981]. The latter authors reported that the electric field signature around auroral arcs in the ionosphere is quite reproducible.

Many of the foregoing matters are considered in this paper.

DESCRIPTION OF THE INSTRUMENTATION

The X ray imaging spectrometer was part of the Stimulated Emission of Energetic Particles (SEEP) payload on the S81-1 spacecraft [*Calvert et al.*, 1985; *Voss et al.*, 1988]. The satellite was three-axis stabilized in a Sun-synchronous 1030 LT and 2230 LT polar orbit at low altitude (170–280 km). The X ray instrument consisted of a position-sensitive proportional counter using a pinhole camera technique to form a one-dimensional 16-pixel image. The counter was filled with xenon gas, sensitive over the energy range 4–40 keV, and had an effective area of 590 cm^2. The X ray field of view was maintained by the 2 cm × 15 cm entrance aperture to provide an overall geometric factor of ~ 6 cm^2 sr (~ 0.4 cm^2 sr per pixel). The spectrometer was oriented in a forward and downward

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X Ray Spectral Images of Energetic Electrons Precipitating in the Auroral Zone

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X rays from the Earth's auroral zone are produced by the precipitation of electrons with kilovolt energies. We have used an imaging X ray spectrometer to observe this radiation over a ~500-km field of view divided into 16 pixels. The observations were made by an experiment on the S81-1 satellite (SEEP: Stimulated Emission of Energetic Particles) during June 1982. Using high spectral resolution 4- to 40-keV X ray data, we have calculated the flux and spectral slope of the precipitating electrons. We have conducted, for the first time, a systematic survey of the characteristics of electron spectra in a large number of individual X ray features. Most of the precipitation is confined to well-defined locations, arcs or isolated patches, separated by regions where no X ray flux was detected. Narrow features are typical for energetic electrons above 5 keV, in contrast to lower-energy electrons, which may produce relatively diffuse optical images. These X ray images have produced two-dimensional maps of precipitation which show no trends of spectral hardness with position, while on the same spatial scales there are order of magnitude changes in the flux of precipitating electrons.

INTRODUCTION

Precipitation of electrons with energies of kilovolts into the atmosphere is a major source of ionization in the Earth's auroral zones. The precipitation has been studied by a variety of experimental techniques. Estimates of the flux and spectrum of precipitating electrons have been derived from direct measurements of the electron flux at satellite altitudes [*Meng et al.*, 1978; *Wallis et al.*, 1979]; from satellite X ray measurements [*Imhof et al.*, 1974; *Mizera et al.*, 1984]; from satellite photometry [*Mizera et al.*, 1978]; from balloon- and rocket-borne X ray observations [*Kremser et al.*, 1986; *Goldberg et al.*, 1982]; from ground-based photometry [*Eather et al.*, 1976]; and from radar profiles of the ionization [*Vondrak and Robinson*, 1985]. Particle detector measurements have shown that precipitating electron spectra are often Maxwellian with characteristic energies of a few keV [*Evans and Moore*, 1979; *Kremser et al.*, 1986] and energy fluxes averaging 1–8 ergs/cm^2 s [*Spiro et al.*, 1982; *Fuller-Rowell and Evans*, 1987; *Hardy et al.*, 1987] depending on geomagnetic latitude, magnetic local time, and geomagnetic activity.

The comparison between the X ray flux measured by satellite instrumentation and the X ray flux calculated from the precipitating electron flux measured by the same spacecraft has been carried out by *Imhof et al.* [1974] and *Mizera et al.* [1978]. Their papers demonstrated good agreement and established that bremsstrahlung X ray measurements can remotely sense electron precipitation in the auroral zone. However, these papers have not done the inverse, to take X ray observations and infer the flux and spectrum of precipitating electrons from it. *Rosenberg et al.* [1987] inferred an electron spectrum from a single X ray spectral measurement made by the Defense Meteorological Satellite Program (DMSP) F6 instrument. At higher X ray energies, 20–120 keV, *Imhof* [1981] fitted electron spectral slopes to a set of simultaneous X ray spectra in six magnetic local time zones measured remotely by the P78-1 satellite; he used the calculations of *Walt et al.* [1979] to convert from X ray spectral shape to electron spectral slope.

X ray images provide a different perspective on the precipitation process from that given by direct particle measurements. Each pixel is an average over its field of view, an extended area, whereas a particle detector samples the magnetic field line passing through the point of observation. X rays originate in the precipitation region; they do not require pitch angle information to map electrons along field lines to the precipitation zone. Thus X rays are well suited to mapping electron precipitation over extended areas, whereas particle detectors can give detailed measurements of the local environment.

In this paper we have, for the first time, used X ray measurements by a satellite to produce a systematic survey of the spectra of the precipitating auroral electrons, which are the origin of the X rays. The measurements were obtained using an imaging proportional counter on the S81-1 satellite during June 1982. The overall set of data consists of approximately 800 individual spectra from 58 X ray emitting regions. The morphological structures in which the precipitation occurred were either isolated patches [*Imhof et al.*, 1988] or arclike features in the auroral zone. In addition, we will present ionization and ion density profiles, which can be readily calculated once the electron spectrum has been inferred. We will conclude with two-dimensional maps showing the flux of precipitating energetic electrons and the characteristic energy of the electrons as functions of location. At the present time, to obtain resolution both in position and in electron energy, bremsstrahlung X ray imaging of electron precipitation is the only proven imaging technique.

The next section describes the instrumentation of this experiment. Section 3 gives some examples of the X ray data. The events in that section will be used to demonstrate the types of analysis carried out on all of the X ray features in this survey. Section 4 gives a brief outline of the techniques used to infer the electron spectra from the X ray data. Section 5 gives the results of the spectral analysis techniques for typical arcs and isolated patches. In the following section we show ionization profiles which can be calculated from the

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