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Lightning-induced electron precipitation

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The broadband very low frequency (VLF, 0.3–30 kHz) radiation from lightning propagates in the Earth–ionosphere cavity as impulsive signals (spherics) and in the dispersive plasma regions of the ionosphere and magnetosphere it propagates as tones of descending or rising frequency (whistlers)[1]. VLF radio waves propagating in the magnetospheric plasma scatter energetic electrons by whistler-mode wave–particle interactions (cyclotron resonance) into the atmosphere[2–6]. These electrons, through collisions with the atmospheric constituents, cause localized ionization, conductivity enhancement, visual and ultraviolet light emissions, and bremsstrahlung X rays. We have reported previously on the precipitation of energetic electrons from the radiation belts by the controlled injection from the ground of VLF radio waves[7,8]. Here we report the first satellite measurements of electron precipitation by lightning. The measured energy deposition of these conspicuous lightning-induced electron precipitation (LEP) bursts ($\sim 10^{-3}$ erg cm^{-2}) is sufficient to deplete the Earth's radiation belts and to alter subionospheric radiowave propagation ($\lesssim$1 MHz). A one-to-one correlation is found between ground-based measurements of VLF spherics and whistlers at Palmer, Antarctica, and low-altitude satellite (S81-1) measurements of precipitating energetic electrons.

Detailed measurements of the pulse shape, spectrum, and pitch angle distribution of LEP events have not previously been obtained nor have direct satellite or ground-based measurements of LEP events been obtained within the plasmasphere where most VLF whistler activity occurs[9]. The plasmasphere (average magnetic invariant latitude $\leq 60°$) is characterized by cold plasma densities of 10^2-10^4 electrons cm^{-3} and is the region of the magnetosphere which contains the bulk of the radiation belts. The only *in situ* measurement of lightning-induced electron precipitation that we are aware of was reported by Rycroft[10] using rocket data. He observed a single electron burst event having the proper time relationship to an associated whistler and explained the observation as a gyro resonant interaction between ~100 keV electrons and a $\frac{1}{2}$-hop whistler taking place in the magnetospheric equatorial plane. Our *in situ* satellite observations confirm this initial rocket measurement by establishing a one-to-one correlation with a series of strong electron burst events and clarify the details of the precipitating electron temporal behaviour. Electron precipitation due to whistler-triggered emissions outside of the plasmasphere has been observed with balloon-borne X-ray detectors[6] and ground-based photometers[11,12]. Indirect evidence of LEP events within the plasmasphere has been derived from amplitude and phase perturbations in VLF signals propagating in the Earth–ionosphere waveguide[13,14].

High sensitivity measurements and fine-resolution energy spectra ($2 < E < 1{,}000$ keV) of the prominent LEP bursts were obtained with a cooled solid-state spectrometer array[15] included as part of the stimulated emissions of energetic particles (SEEP) experiment on the three-axis stabilized, low-altitude (~230 km) S81-1 satellite. The trapped energetic (TE) electron spectrometer (±20° field of view) was aligned perpendicularly to the orbit plane and during these observations was at an angle of 89° to the local magnetic field line. The TE detector had a geometrical factor of 0.17 cm^2 sr and was cooled (−120 °C) to achieve a system noise resolution of 1.2 keV FWHM. An identical detector was positioned to observe electrons with central pitch angles (α) of 52°. The medium energy (ME), precipitating electron spectrometer (±30° field of view) was aligned to the zenith direction and during these observations was at an angle of 25° to the local magnetic field line. The ME geometrical factor was 2.47 cm^2 sr.

Seven LEP events recorded on 9 September 1982 with the SEEP experiment TE particle spectrometer are shown in Fig. 1 (A-G) with the simultaneous VLF spectra received at Palmer, Antarctica ($L \approx 2.3$). These LEP event signatures are interpreted as follows. The whistler wave in passing through the magnetosphere from north to south alters the pitch angles of energetic trapped electrons which are moving northward and can, therefore, resonate with the VLF wave. This interaction reduces the pitch angles of some of the electrons, lowers their mirror points below the satellite altitude, and produces the first electron pulse of the event. Some of these electrons are then magnetically reflected and some are scattered by the atmosphere, resulting in an electron bunch moving to the Southern Hemisphere where the lower mirroring altitude (due to the South Atlantic anomaly) causes the electrons to encounter the atmosphere. Some electrons are backscattered by the atmosphere and return to the Northern Hemisphere where they are observed as the second pulse in the event. Subsequent reflections and backscattering in the Northern and Southern Hemispheres produce the train of pulses of diminishing intensity which makes up the individual events shown in Figs 1 and 2. These measurements were made 3 days after the strong magnetic storm ($D_{\mathrm{st}} = -297$) of 6 September 1982. Magnetic storms of this intensity are known to inject electrons which diffuse into the slot region ($2 < L < 3$) of the radiation belt several days after the storm onset[16,17].

In the strong LEP events A, D, and E, electron fluxes are observed to increase rapidly in strength, about 100 times background, in <200 ms. The envelopes of the individual pulses then decay relatively slowly to background levels over several seconds. Event G is a factor of 10 above background and event F about three times background. Events B and C are relatively weak on the integral energy display of Fig. 1 but are more prominent in the differential energy spectrum ($120 < E < 140$ keV). The reason why the multiflash LEP event E does not show echo pulses may be due to the superposition of four closely spaced LEP bursts. The flux measured with the ME detector ($\alpha \approx 25°$) is a factor of ~10 less than the flux measured with the TE detector ($\alpha \approx 89°$) indicating an anisotropic pitch angle distribution peaked near 90° at the satellite altitude. VLF spectra of lightning generated spherics and whistlers were detected in the conjugate hemisphere at Palmer Station, Antarctica, (65° S, 64° W) and are shown in Fig. 1*a*. The uniform transition in VLF wave intensity at ~1.9 kHz indicates a well defined Earth–ionosphere waveguide cutoff frequency. The scaled spherics and whistlers are shown beneath the VLF spectrogram. The dashed portion of a scaled whistler curve is extrapolated based on the observed solid portion and the known properties of more completely defined events such as *F*. The conjugate of the SEEP satellite (60° S, 98° W) is 34° to the west of Palmer and thus the VLF spectrogram intensity at Palmer is not simply related to the magnetospheric whistler intensity nor to the flux of precipitating electrons.

Whistler-dispersion techniques[1] are used to identify the spherics that precede the delayed whistler signal on the VLF spectrogram. Event E has four similar whistler traces within a 1-s period and is consistent with multiflash lightning. Event C also has two lightning flashes associated with it. An important observation is that the spherics precede the peak of each LEP event by the expected time interval (≈ 0.4 s) for all seven cases.

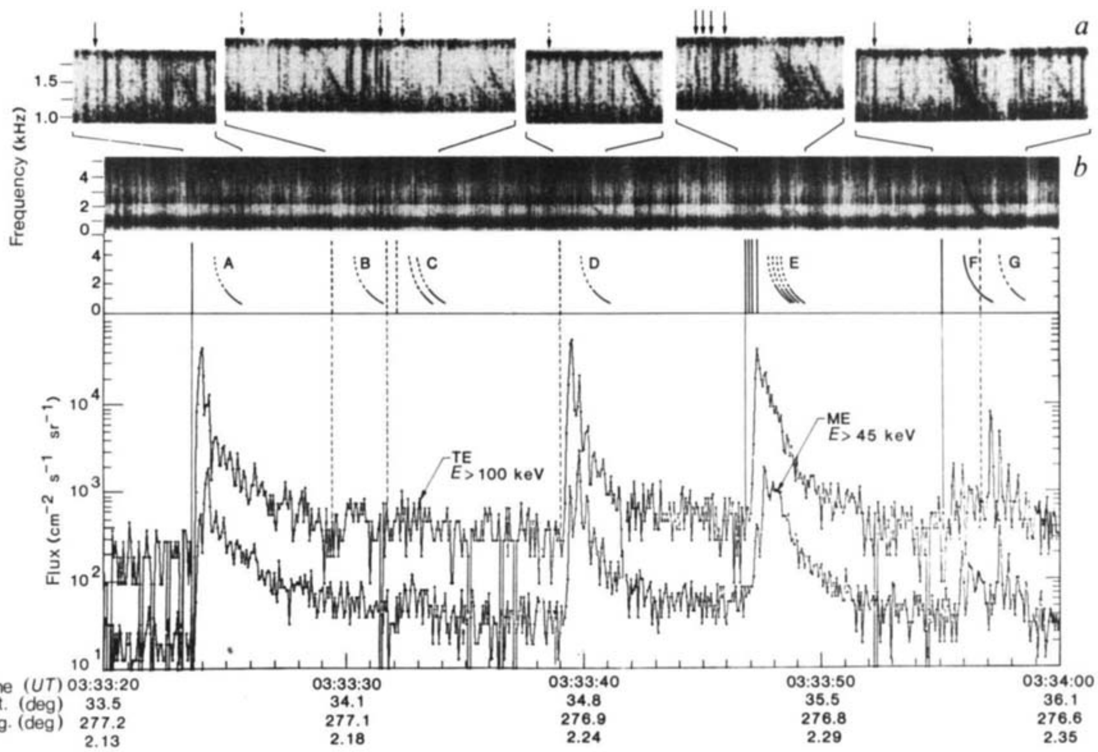

Fig. 1 Energetic electron measurements obtained with the S81-1 satellite are correlated one-to-one with concurrent ground-based VLF whistlers at Palmer Station, Antarctica (65° S, 64° W, $L \simeq 2.3$). Panels *a* and *b* show the VLF spectrograms and the scaled whistlers and spherics. The uppermost insets show the Palmer VLF data with an expanded time scale for the seven LEP events. The strong energetic electron bursts labelled A, D and E have peak fluxes that are 100 times background levels. The sampling interval for the energetic particle measurements is 64 ms. The solid lines and arrows represent spherics that were directly identified on these (and other) records, while the dashed lines represent time estimates based on evidence of essentially identical dispersion properties in all events.

Further evidence for the triggering of precipitation by lightning is given by the LEP pulse shapes and spectra. In the pulse shapes of LEP events A, D, F and G, repetitive pulses of constant period and decaying amplitude that follow the LEP peak are conspicuous. Figure 2 shows LEP events F and G on an expanded scale with the associated whistler signals and the subionospherically propagating signals from the transmitter NAA as received at Palmer. The detailed characteristics of the LEP events shown in Fig. 2 include: (1) the rapid rise of electron flux; (2) the subsequent and relatively slow decay of the flux; (3) the in-phase and repetitive pulses on the TE and ME detector (labelled 1-3 for event F and 1-5 for event G); (4) the greater intensity of the near 90° pitch angle flux (TE) compared with the near 0° pitch angle flux (ME); and (5) the weak or completely absent first pulse on the ME spectrometer (indicating a high ratio of drift-loss-cone to direct bounce-loss-cone flux) compared with the subsequent pulses (labelled 2-5 for event G).

A pulse period of 0.32s is associated with pulses 1-7 of event A. This period agrees with the bounce time of relativistic electrons (~150 keV) echoing between conjugate hemispheres at $L = 2.1$. For 175-keV electrons, the relativistic velocity is $0.67c$ and for 125 keV electrons $0.60\,c$, where c is the velocity of light. As the velocity approaches c the bounce period becomes less sensitive to electron energy variations. For the above energy difference, about five bounce periods (pulses) can occur before the 175-keV electrons are 180° out of phase with the 125-keV electrons. The pulse period of LEP event G at $L = 2.3$ is 0.38 s. This longer period relative to LEP event A agrees with the longer path length of relativistic electrons echoing between conjugate hemispheres at $L = 2.3$ instead of $L = 2.1$.

Examination of the electron energy spectra of LEP events A-G indicates a prominent but broad peak in electron energy between 80 and 200 keV that decreases in energy with increasing L. From comparison of the travel time characteristics of the 9 September 1982, whistlers with similar but more completely defined events recorded on another day at Palmer when whistler-associated precipitation was observed[18], the equatorial electron density at $L = 2.1$ is estimated to have been 3,200 electrons cm^{-3}. Assuming ducted propagation the VLF wave frequency would be ~4 kHz based on an equatorial gyroresonant interaction with 150 keV electrons. This frequency is in the upper region of the more broadly defined whistlers, such as event F.

Figure 2*a* shows a small perturbation in the signal received at Palmer from NAA (propagating in the Earth-ionosphere waveguide) which is coincident with the strong whistler and weak LEP burst F. The raw data show the 17.8-kHz signal intensity using a 300-Hz bandwidth filter. Also shown are the smoothed curves of the raw data (dashed lines) outside of the rapid transition interval (±0.5 s) that were obtained using a 2.4 s averaging filter. The amplitude of the NAA transmitter signal received at Palmer exhibits a fast decrease (< 1.5 s) followed by a slow recovery (~10 s). Such a signal perturbation or 'Trimpi' event is associated with lightning-induced electron precipitation which modifies the ionosphere at the ~80 km reflection altitude[13,14]. Considered in isolation, this event is weak because of atmospheric noise at the NAA frequency. However, it is similar in form to a series of stronger events that occurred within several minutes preceding and following the period of satellite data. The strong whistler event F and associated Trimpi event recorded at Palmer are consistent with a relatively strong LEP burst occurring near Palmer. For the other six relatively weak whistler signals no Trimpi events were detected although strong electron precipitation is evident in the SEEP detectors for events A, D, E and G. The simultaneous electron precipitation at the SEEP satellite and near Palmer (Trimpi) which are separated in longitude by 2,000 km, for event F, suggest that a single lightning flash can precipitate electrons at two widely separated locations.

The electron precipitation energy fluxes are estimated to be about 10^2-10^5 times the wave energy flux at the equatorial plane, indicating that only a little VLF signal energy is required to perturb the relativistic electrons near the edge of the loss cone enough to cause precipitation[3]. The energy fluxes reported here are consistent with suggestions that whistlers may cause a

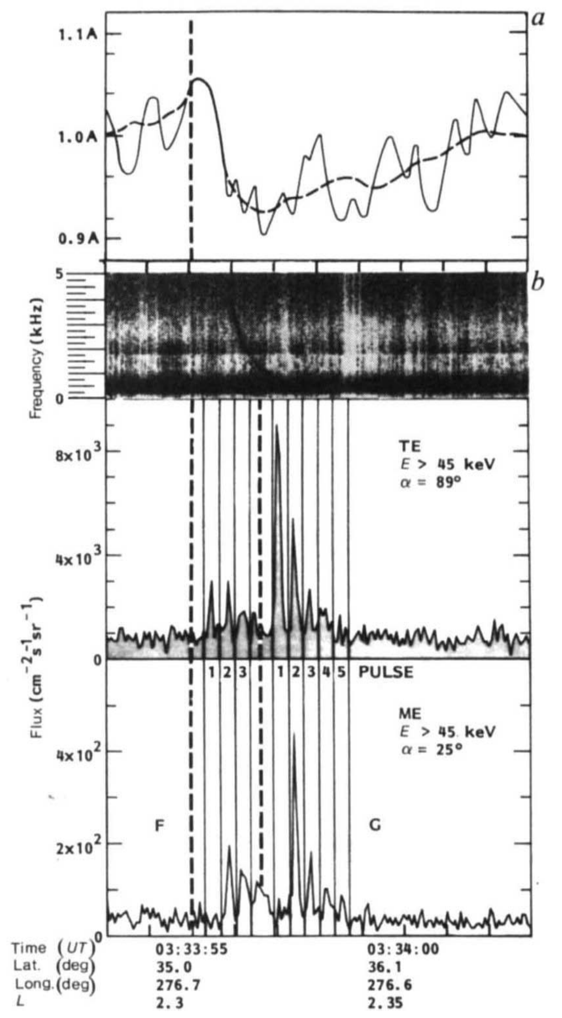

Fig. 2 Expanded view of lightning-induced electron precipitation (LEP) events F and G. The repetitive pulses of constant period labelled 1 to 5 are consistent with the echo period for electrons mirroring between conjugate hemispheres. The vertical dashed line indicates the calculated time of the lightning flash. Panels *a* and *b* show the simultaneous whistler spectrogram and the amplitude of signals received at Palmer from NAA.

significant loss of radiation belt electrons[3-5,19,20,22]. Assuming that the slot regions of the radiation belts are initially filled after a magnetic storm with an omnidirectional flux of 10^8 electrons $cm^{-2}\ s^{-1}$ for $E > 100$ keV at $L = 2.3$, a single LEP burst (such as event D) can empty ~0.001% of the belt in the region covered by the burst magnetic field lines.

The observations of LEP events provide direct evidence of an important coupling mechanism between terrestrial lightning and relativistic radiation belt electron precipitation. Further study should clarify details of the wave-particle interaction since wide ranges of VLF signal strength and frequencies are present. The global mapping of LEP events can also provide an insight into the penetration of wave energy through the ionosphere and its propagation in the magnetosphere. The role of LEP events in the overall loss rates of trapped electrons is uncertain, because the frequency of occurrence of these events and their relative importance in comparison, for example, with plasmaspheric hiss[21] is not well known. However, a substantial amount of electrons can be removed in a single event, and additional electron losses can be expected to result from an enhancement of the effective pitch angle diffusion coefficient by whistler waves.

The Lockheed Palo Alto Research Laboratory portion of the SEEP experiment was sponsored by the Office of Naval Research (contrast N00014-79-C-0824). Launch and orbital support were provided by the Air Force Space Test Program Office. Much of the data analysis was performed under the Lockheed Independent Research Program. We thank Dr D. P. Cauffman for program management of the satellite payload; the payload system engineer, Mr S. J. Battel; and Dr D. W. Datlowe for help in processing the data. The Stanford University effort in SEEP was supported by ONR grant N00014-82-K-0489 and by the Division of Polar Program of the NSF under grant DPP82-17820 for the Palmer Station VLF program.

Received 21 June; accepted 3 October 1984.

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A new radiation source for the infrared region

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Spectroscopy in the far-infrared and millimetre-microwave regions has always been hampered by the lack of intense broad-band sources. After several predictions[1-4] suggesting the possibility of obtaining improved infrared fluxes from an electron source, the Daresbury (SERC) synchrotron storage ring (SRS) has now been shown to produce an intense and very bright source of infrared photons. The infrared port (IR-13(1)) at Daresbury will provide scientists interested in the microscopic structure and dynamics of materials with a radiation source having several unique properties. As well as these properties, we describe here the work that has been done, since January 1984, in characterizing the infrared beam and suggest some wide-ranging potential experimental applications.

Because the photon beam is composed of electromagnetic radiation emitted by a highly relativistic electron beam[5], the radiation is highly collimated in the forward direction and is strongly linearly-polarized in the orbit plane. Furthermore, it provides a well-defined train of pulses of radiation[6] of ~200 ps in width with a period of either 320 ns (for a single electron bunch) or 2 ns (for 160 electron bunches). The pulse width and shape are entirely independent of frequency, and the inherent photon noise level is expected to be very low compared with that of black-body sources. The beam lifetime is 8-10 h at 2 GeV electron energy. Although the SRS is more intense (in terms of photons emitted per second) than a black-body emitter only in the far-infrared region (below ~50 cm^{-1}), its other advantages—especially its brightness (watts per unit area-solid angle) and its precise time structure—are manifest throughout the infrared.