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LIGHTNING-ASSOCIATED PRECIPITATION OF MeV ELECTRONS FROM THE INNER RADIATION BELT

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Abstract. Transient perturbations of subionospheric very low frequency (VLF) radiowave signals provide new evidence for lightning-induced electron precipitation (LEP) events involving short (< 1 s) bursts of > 1 MeV electrons from the earth's inner radiation belt at $L \leq 1.8$. The signal amplitude changes are attributed to increased absorption in the earth-ionosphere waveguide and/or alterations of the waveguide mode structure due to localized secondary ionization enhancements produced in the nighttime lower ionosphere and the mesosphere by the precipitating electrons. The otherwise stably trapped electrons are believed to be scattered in pitch angle during cyclotron resonant interactions in the magnetosphere with the lightning-generated whistler waves. That some precipitation bursts consist partly of MeV electrons is suggested by (i) confinement of the perturbed subionospheric signal path to low magnetic latitudes ($L \leq 1.8$), for which corresponding electron energies for gyroresonance with typical whistler-wave frequencies in the magnetosphere are > 1 MeV, and (ii) the temporal signatures of the perturbation events, which often exhibit an unusually rapid initial recovery (time constant of $\tau < 1$ s) followed by further recovery at rates believed characteristic of less energetic events ($\tau \sim$ 5–20 s). The latter is interpreted as a manifestation of the rapid variation with altitude of the effective loss rate for excess ionization over an exceptionally wide range of mesospheric altitudes (40-70 km) penetrated by the > 1 MeV electrons.

INTRODUCTION

Lightning-induced precipitation of energetic radiation belt electrons has recently been extensively investigated by means of the resulting subionospheric VLF signal perturbations [*Inan and Carpenter*, 1987, and references therein], as well as satellite and rocket-based observation [*Voss et al.*, 1984; *Goldberg et al*, 1986]. Observations inside the plasmasphere have identified the L-shell range of $2 < L < 3$ as a region of prime activity for whistler-induced precipitation 40-300 keV electrons [*Carpenter and Inan*, 1987; *Imhof et al*, 1986].

In this paper, we present the first evidence of the lightning-associated precipitation of > 1 MeV electrons out of the inner radiation belt at $L \leq 1.8$. The evidence consists of the observation of characteristic VLF signal perturbations on a subionospheric signal path that lies entirely on $L \leq 1.8$. That the electron energies involved are in the MeV range is inferred from (i) the fact that gyroresonant electron energies for typical whistler wave frequencies (200 Hz to 6 kHz) are in the MeV range for $L \leq 1.8$, and (ii) the unusually rapid initial recovery ex-

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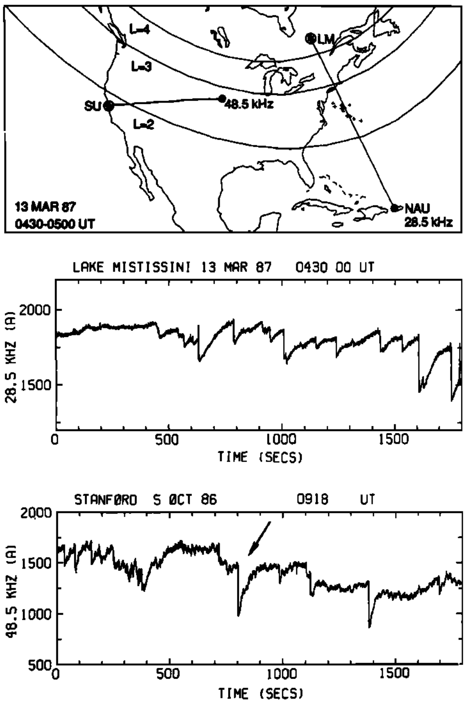

Fig. 1. Examples of LEP events believed to consist of < 300 keV electrons observed as subionospheric VLF amplitude changes at mid latitudes. The loci (at 100 km) of the feet of the earth's magnetic field lines crossing the equatorial plane at 2, 3, and 4 earth radii (L=2, 3, and 4) are shown superimposed. The top panel shows the great-circle propagation paths from a 48.5 kHz transmitter in Silver Creek, Nebraska to Stanford University (SU) and from the 28.5 kHz NAU transmitter in Puerto Rico to Lake Mistissini (LM), Quebec. The location of lightning events as detected by the east coast lightning detection network during 0430–0500 UT on 13 March 1987 are shown as +'s. The signal amplitude records shown in the middle and bottom panels cover 30-minute periods starting at the UT indicated. For the 5 Oct 86 case, absolute time is $\sim$ 0918 UT within ± 1 min. The data shows signal intensity within a $\sim$ 300 Hz bandwidth, time-averaged over $\sim$ 0.64 s. The vertical axes show signal strength (A) in linear arbitrary units, with $A = 0$ representing absence of signal. The event marked with an arrow is shown with higher resolution in Figure 3.

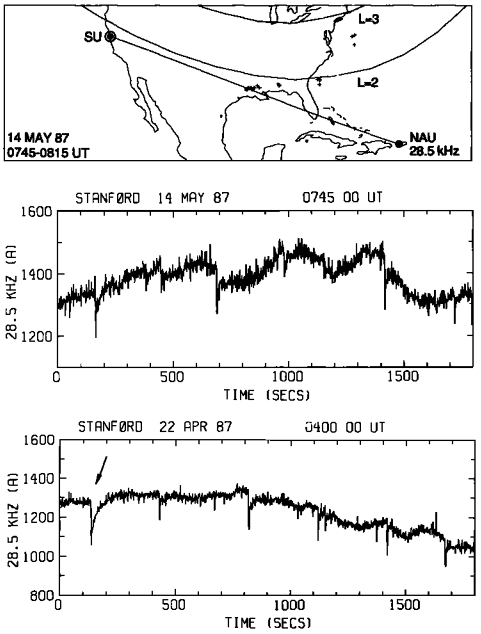

Fig. 2. Examples of LEP events consisting partly of MeV electrons and observed at $L < 1.8$. The top panel shows the subionospheric propagation path and the location of lightning flashes to ground (+'s) detected on 14 May 1987. For 22 April 1987, lightning activity was reported [Ref. 1] in southwestern Texas, within ~ 50 km of the great circle path, and outside the range of the east coast lightning detection network. The data shows signal intensity within a ~ 300 Hz bandwidth, time-averaged over ~ 1.28 s. The format of the figure is otherwise similar to that of Figure 1. The event marked with an arrow is shown with higher resolution in Figure 3.

hibited by the observed perturbations which is attributed to the relatively short effective loss rate for excess ionization at 40-70 km altitudes penetrated by the MeV electrons.

EXPERIMENTAL RESULTS

Figure 1 shows examples of lightning-associated subionospheric VLF signal amplitude changes of the type previously observed at mid-latitudes (i.e., $2 < L < 3$). Lightning flashes to ground (+'s) were observed by the SUNY-Albany lightning detection network [*Orville et al.*, 1983] near the perturbed signal path in the first case (13 Mar 87) in which ~ 50% of the VLF amplitude changes are time correlated with individual flashes detected by the network as well as with radio atmospherics detected by the VLF receiver [*Inan et al.*, 1987*a*]. Other events were also time correlated with spherics and may have been caused by ground flashes missed by the network or by intracloud flashes, which are excluded by the network, in the storm area indicated. In the second case (5 Oct 86), the signal path is outside the coverage of the east-coast lightning network; however, lightning-induced radio atmospherics were observed at Stanford in time-correlation with the amplitude changes [*Inan et al.*, 1987*b*]. Previously reported ground- [*Inan and Carpenter*, 1987] and satellite-based [*Voss et al.*, 1984] measurements suggest that the amplitude changes of the type shown in Figure 1 are induced by short (< 1 s) bursts of electrons with energies up to 300 keV. Exponential recovery with a time constant of $\tau \sim$ 5–20 s is believed to represent the effective loss rate at nighttime for excess ionization at the 70–90 km D-region altitudes to which 40-300 keV electrons can penetrate [*Gledhill*, 1986; *Dingle and Carpenter*, 1981].

Figure 2 shows examples of a new type of event detected at $L < 2$. In the first case (14 May 87) lightning was detected on the signal path as shown. In the second case (22 Apr 87), thunderstorm activity was reported in southwest Texas, within ~ 50 km of the signal path and outside the coverage of the network [Ref. 1]. The events in Figure 2 exhibit unusual temporal signatures, characterized by a rapid initial recovery followed by a decreasing recovery rate, as compared with a typical signature at high resolution in Figure 3. This signature is interpreted as resulting from the height-integrated, time-varying effects of loss processes taking place over an exceptionally wide range (40-90 km) of altitudes penetrated by > 1 MeV precipitating electrons [*Gledhill*, 1986].

THEORETICAL MODEL

To test the above hypothesis, a model of the overall process was constructed, involving (i) the whistler-particle scattering near the geomagnetic equator, (ii) the generation of secondary ionization in the lower ionosphere as a result of the incident flux, (iii) the decay of the extra ionization back to the ambient levels, and (iv) the incremental absorption of a subionospheric radio signal resulting from the enhanced ionization, leading to a characteristic signal amplitude variation as the ionization decays.

Considering the electron energies required for gyroresonance with typical whistler frequencies of 0.2–6.0 kHz, the presence of MeV electrons is consistent with the location of the perturbed signal path at $L \leq 1.8$. For representative [*Park et al.*, 1978; *Brace and Theis*, 1974]

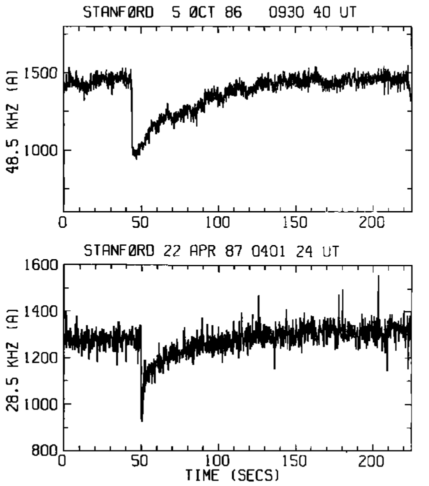

Fig. 3. Expanded records of selected events (marked with arrows) from Figures 1 and 2, illustrating the temporal signature of the LEP events involving lower (< 300 keV) energy electrons as observed at mid-latitudes ($L > 2$) (top panel) in comparison with those including MeV electrons observed typically at low latitudes ($L < 2$). The data shows signal intensity within a ~ 300 Hz bandwidth, time-averaged over ~ 0.16 s. For the top panel, absolute time is ~930:40 UT within ± 1–min.

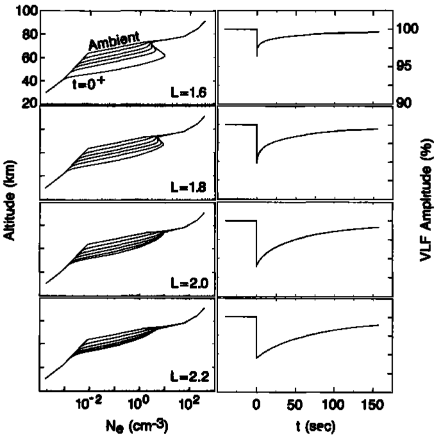

Fig. 4. Ionization profiles and associated VLF amplitude changes resulting from simulated LEP bursts precipitated by a 0.2–6 kHz whistler wave over a range of L-shells. The burst duration and average flux were assumed to be 0.2 s and 10^{-3} ergs cm^{-2} s^{-1} respectively. On the left, altitude profiles of electron density show secondary ionization from each burst and the recovery to ambient nighttime levels at $t = 0$, 1, 5, 20, and 100 seconds after the perturbation. Corresponding VLF signal amplitude variations computed on the basis of height-integrated vertical incidence absorption through the enhanced ionization region are shown on the right.

equatorial cold plasma densities of 4600 and 1100 cm^{-3} at $L = 1.8$ and 2.5 respectively, electrons of > 1 MeV energies resonate with <0.25 kHz at L=2.5 compared with <1.4 kHz at L=1.8.

Assuming equilibrium conditions for the energy and L-dependence of the trapped particle flux [*Lyons and Thorne*, 1973], linear scattering [*Kennel and Petschek*, 1966; *Inan*, 1987] with an interaction region of fixed length, and constant whistler wave intensity over the 0.2–6 kHz range, the precipitated flux is proportional to $(mv_{\|})^{-1}$, where m is the relativistic electron mass and $v_{\|}$ is the particle velocity alongs the earth's magnetic field. The total energy flux and the pulse duration of the LEP bursts were assumed to be $\sim 10^{-3}$ ergs cm^{-2} s^{-1} and 0.2 s, respectively, consistent with previously reported cases [*Chang and Inan*, 1985; *Inan and Carpenter*, 1987; *Voss et al.*, 1984] observed at $L > 2$. These assumptions allow the determination of the energy spectrum of the LEP burst in the absence of information on the whistler wave intensity in the magnetosphere.

For the production of the secondary ionization, we assumed that the depth of penetration is determined by the incident particle energy and atmospheric pressure [*Rees*, 1963; *Rishbeth and Garriott*, 1969]; published production profiles were extrapolated to energies of a few MeV. The recovery of the ionization was assumed to be governed by an altitude dependent effective loss rate, as determined empirically from many different experimental measurements [*Gledhill*, 1986]. The ambient nighttime D-region profile was taken to be representative of geomagnetically quiet times [*Reagan, et al.*, 1981; *Helliwell*, 1965]. Secondary ionization profiles computed on this basis as a function of time for $L = 1.6, 1.8, 2.0$ and 2.2 are shown in Figure 4.

In general, the resultant VLF signal intensity at the receiver is not easily related to localized ionization profiles due to the complexity of multiple-mode subionospheric VLF propagation [*Tolstoy et al.*, 1986]. Thus, the absolute value of the amplitude changes cannot be determined without additional information. Nevertheless, the temporal signature of the observed amplitude variation can be expected to resemble that for a single waveguide mode. As an estimate of the signature, we use the height-integrated absorption [*Helliwell*, 1965] through the enhanced ionization region for vertical incidence. The computed VLF amplitude variations corresponding to the density for $L = 1.6, 1.8, 2.0$ and 2.2 are given in Figure 4. The predicted signatures compare well with the data shown in Figure 3, especially for the L-dependence. Quantitative differences can be attributed to deviation from equilibrium of the L-dependence of the trapped particle flux and variations in whistler wave spectrum. Nevertheless, the fact that the temporal signature is sensitively dependent on the energy spectrum of the incident flux is interesting, and provides support for our hypothesis that an MeV component is present in some of the LEP bursts.

Note that the purpose of the theoretical model constructed here is merely to compare the temporal variation of the recovery signatures expected on different L-shells. The comparison of the absolute level of the signal amplitude changes given in Figure 4 is not meaningful in view of the fact that the absolute flux level as well as the size and distribution of the perturbed region(s) and their relationship to the great circle path(s) may well vary with L-shell. Since we do not intend to compare absolute values of amplitude changes, the assumption of an energy flux level of 10^{-3} ergs cm^{-2} s^{-1} is not a critical one. Similarly, the intercomparison of the recovery signatures is not likely to depend critically on our use of vertical incidence absorption to compute the percentage signal amplitude changes. This assumption avoids the problem of having to know the horizontal dimensions of the precipitation region(s).

DISCUSSION

In terms of occurrence characteristics, one or more LEP events on the 28.5 kHz NAU-SU path (see Figure 2) were observed on 17 different days from mid-March to mid-May 1987. Events on 13 of these days exhibited fast recovery. During the same period LEP events (not necessarily involving MeV electrons) were observed on 13 days on a 21.4 kHz signal path between Maryland ($L \sim 2.6$) and Stanford ($L \sim 1.8$). LEP events believed to involve MeV electrons are also on occasion observed on this path, as well as others that lie mostly at $L > 2$. Such events might occur when freshly injected MeV electrons appear outside the inner radiation belt, and/or when the whistler waves excited by lightning are particularly intense at $\leq$ 500 Hz. Events observed on the NAU-SU path that do not exhibit fast initial recoveries may in turn be due to a reduction of MeV electron flux in the inner belt and/or a concentration of whistler wave energy at relatively higher frequencies. That the NAU-SU path has been particularly active in terms of event occurrence may partly be due to the fact that lightning activity commonly occurs near the mid-point of the propagation path, where it might be most effective in perturbing the amplitude of the VLF signal.

The presence of lightning activity near the NAU-SU path (in the Gulf Coast region) suggests association of the observed VLF perturbations with lightning. On 5 selected days (including 14 May 87, Figure 2) the lightning network reported activity near the NAU-SU path over a period when signatures with rapid recovery were observed at Stanford on the 28.5 kHz NAU signal.

Time correlation between lightning strokes detected by the network and VLF perturbations in this period was less useful. Only a few perturbation onsets occurred within $\sim$ 1 s of detected flashes and vice versa. This result is consistent with the finding of a separate case study [*Inan et al.*, 1987*a*] of a 6-hour sequence of unusually well defined events observed at Lake Mistissini on 13 Mar 87 (see Figure 1) where it was found that $\sim$ 50% of the observed VLF events did not have associated cloud-to-ground flashes. These events were attributed to either intracloud flashes not recorded by the lightning network or ground flashes missed by the network. Furthermore, the case study suggested that lightning flashes beyond $\sim$ 150 km of the subionospheric great circle path are less likely to produce VLF signal perturbations [*Inan et al.*, 1987*a*]. Detailed investigation of the time-correlation between the VLF events and the ground flashes detected by the network must therefore take account of the flash type and location and is beyond the scope of this paper.

The finding of lightning-induced MeV electron precipitation at latitudes as low as $L \sim 1.8$ suggests that similar events might occur in other thunderstorm centers under the inner radiation belt, including tropical areas. In terms of the dynamics of the inner radiation belt, lightning-induced precipitation might be an important contributor to the loss of the stably trapped particles. In terms of the aeronomy of the lower ionosphere and the mesosphere, the MeV electrons deposit their energy over a wide range of altitudes down to $\sim$ 40 km, impulsively modifying the ionization profile of the nighttime lower ionosphere and mesosphere and potentially influencing chemical processes at these altitudes [*Baker et al.*, 1987]. Further experiments, possibly involving VLF measurements on even lower latitude paths, are clearly needed to determine the extent to which events occur well within the inner radiation belt (e.g., $L = 1.6$, see Figure 4). Measurements at multiple receiving locations can potentially be used to better define the occurrence rate and spatial distribution (both small and large scale) of the LEP events with MeV electrons. Bremmstrahlung X rays generated by the penetrating electrons should be detectable from balloons, and riometer measurements of the enhanced absorption of cosmic radio noise in the 40–70 km range might be used to measure the precipitation flux levels.

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