4-05a

LOW-LATITUDE IONOSPHERIC PHYSICS

Proceedings of COSPAR Colloquium on Low-Latitude Ionospheric Physics held in Taipei, Taiwan, 9–12 November, 1993

Edited by

FU-SHONG KUO

Institute of Space Science, National Central University, Chung-Li, Taiwan

PERGAMON

LIGHTNING-INDUCED DISTURBANCES OF THE LOWER IONOSPHERE

U. S. Inan

Space, Telecommunications and Radioscience Laboratory, Stanford University, Stanford, CA 94305, U.S.A.

ABSTRACT

Recent experimental and theoretical work has brought to fore a new class of transient and localized disturbances of the nighttime lower ionosphere (<100 km altitudes) which occur in association with tropospheric lightning discharges. These disturbances are believed to occur in at least two different ways: (i) due to the precipitation of bursts of energetic radiation belt electrons by whistler waves injected into the magnetosphere by lightning discharges, and (ii) due to the direct interaction with the collisional lower ionospheric plasma of the intense electromagnetic (EM) pulses from lightning.

INTRODUCTION

On the average, approximately 100 lightning discharges occur per second over our planet, in approximately 2000 thunderstorm centers which are active at any given time /1/. The EM power released by a cloud-to-ground return lightning stroke may on the average be equivalent to that of a 20 GW isotropic radiator lasting for $\sim$ 100 μs, and corresponding to peak electric fields at 100-km horizontal distances from the source of $\sim$ 10 V/m /2/. In view of such widespread occurrence of lightning, and the intensity of the EM radiation released, it is perhaps not surprising in hindsight that lightning discharges may significantly influence the lower ionosphere. However, experimental evidence concerning the nature and extent of the ionospheric effects of lightning have only recently been available, as discussed below. Theoretical modeling motivated by this experimental evidence has just now begun to clarify the underlying mechanisms and their potential effects on a global scale.

Electromagnetic energy released in lightning discharges leads to significant disturbances of the lower ionosphere in at least two fundamentally different ways. One effect, commonly referred to as Lightning-Induced Electron Precipitation (LEP), occurs as a result of the coupling into the earth's magnetosphere of a relatively small portion of the EM energy from lightning. The wave energy propagates in the whistler-mode between hemispheres in ducts of enhanced ionization and interacts in cyclotron resonance with energetic electrons trapped in the earth's radiation belts. One result of this interaction is the pitch angle scattering of the electrons and their precipitation into the ionosphere. With typical energies at mid-latitudes of > 50 keV, the short (< 1 s) bursts of precipitating electrons are deposited in the lower ionosphere at altitudes < 100 km, creating secondary ionization, x-rays and heat. The second effect, referred to as Lightning-Induced Heating and Ionization, results from the direct electrodynamic coupling of the intense EM pulse itself with the collisional lower ionospheric plasma. The free electrons of the nightime D region are accelerated to energies of several eV dring the passage of the lightning EM pulse, leading to the generation of optical emissions and impact ionization of the neutrals.

The possible precipitation of energetic radiation belt particles due to cyclotron resonance interactions with whistlers was first suggested shortly after the discovery of the belts /3/. However, subsequent work concentrated on the scattering of the electrons by plasmaspheric hiss emissions and experimental evidence of whistler-induced precipitation was not forthcoming for many more years. The possibility of ionization of the ionosphere by lightning was considered shortly after the discovery of the ionosphere /4,5/. However, these early authors considered oversimplified models of the ambient density profile and wave propagation and obtained inconclusive results. Further consideration of the possibility of lightning-induced ionization was to come many years later /6/, driven largely by experimental evidence.

The first evidence for a lightning-induced ionospheric disturbance was in the form of subionospheric VLF perturbations observed in association with ducted magnetospheric whistlers /7/. These perturbations were attributed to secondary ionization in the lower ionosphere produced by the impact of energetic radiation belt electrons which were scattered and precipitated by whistlers, i.e., the phenomenon termed LEP as mentioned above. This hypothesis has been supported and further developed by many later ground-based studies /8,9/, by *in situ* observations of precipitation bursts in association with whistlers and/or lightning /10,11/, and by detailed theoretical interpretation of satellite observations /12/. Figure 1 depicts the LEP process, the resulting ionospheric disturbance and the associated subionospheric perturbation.

The experimental evidence for the direct upward coupling of lightning energy to the lower ionosphere was also in the form of VLF perturbations observed in association with lightning /13/. However, as opposed to LEP events the onsets of which generally occurred 0.3 to 1.0 s after the causative lightning, these perturbations occurred within < 50 ms of lightning or radio atmospherics (see Figure 8 below). The lack of any such measured delay between the lightning discharge and event onsets suggested that lightning-induced electron precipitation may not be the cause of such events. The duration of the event onsets were also unusually rapid, being typically < 50 ms. The lack of a delay and the rapid onsets of these events were respectively recognized by referring to them as *early* and *fast* VLF perturbations /14/. Following a serendipitious observation of lower ionospheric heating by VLF transmitter signals /15,6/ suggested that the early/fast VLF perturbations result from the intense heating of the lower ionospheric plasma by the EM radiation from lightning. Although the elevated electron temperatures exist only as long as the EM pulse from lightning (i.e., 50-100 μs), sufficient extra ionization is produced to cause all of the observed features of the early/fast subionospheric VLF signals /6/. Figure 3 depicts the lightning-induced heating and ionization process and its detection via subionospheric VLF signals.

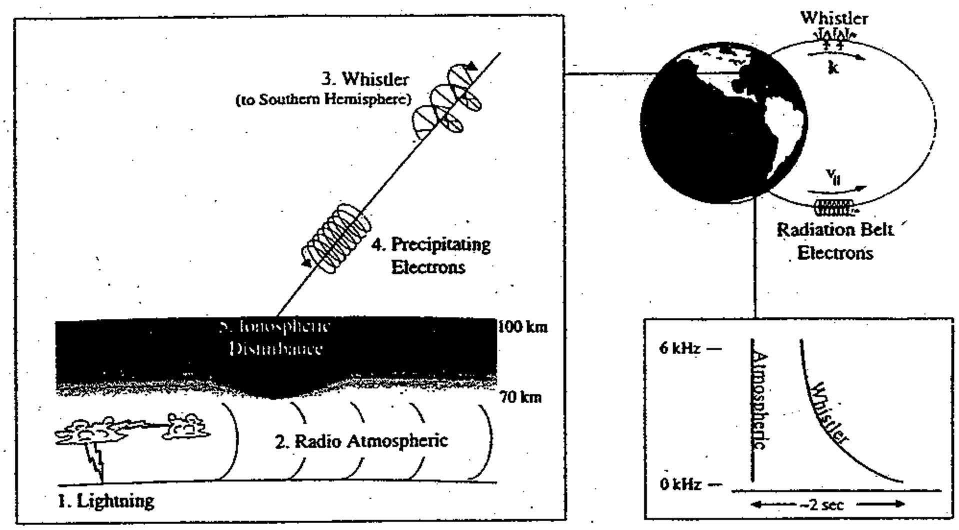

Fig.1. Electron precipitation induced by ducted whistlers. A lightning discharge (1) launches a radio atmospheric, or "sferic" (2), which propagates in the Earth-ionosphere waveguide and is often strong enough to be detectable all over the planet. Enhancements of the plasma above the ionosphere, aligned with the geomagnetic field and known as "ducts," can trap a portion of the sferic energy and cause it to propagate along a field line to the opposite hemisphere as a whistler (3). During its journey the circularly polarized whistler can interact with gyrating energetic radiation belt electrons, scattering them in pitch angle so that some escape from their geomagnetic trap (4). Upon striking the ionosphere, the precipitating electrons cause significant secondary ionization (5). Meanwhile, the whistler emerges from its duct and can be observed, along with the subionospherically propagating 'causative' sferic, with broadband VLF radio equipment in the opposite hemisphere [Figure from /9/].

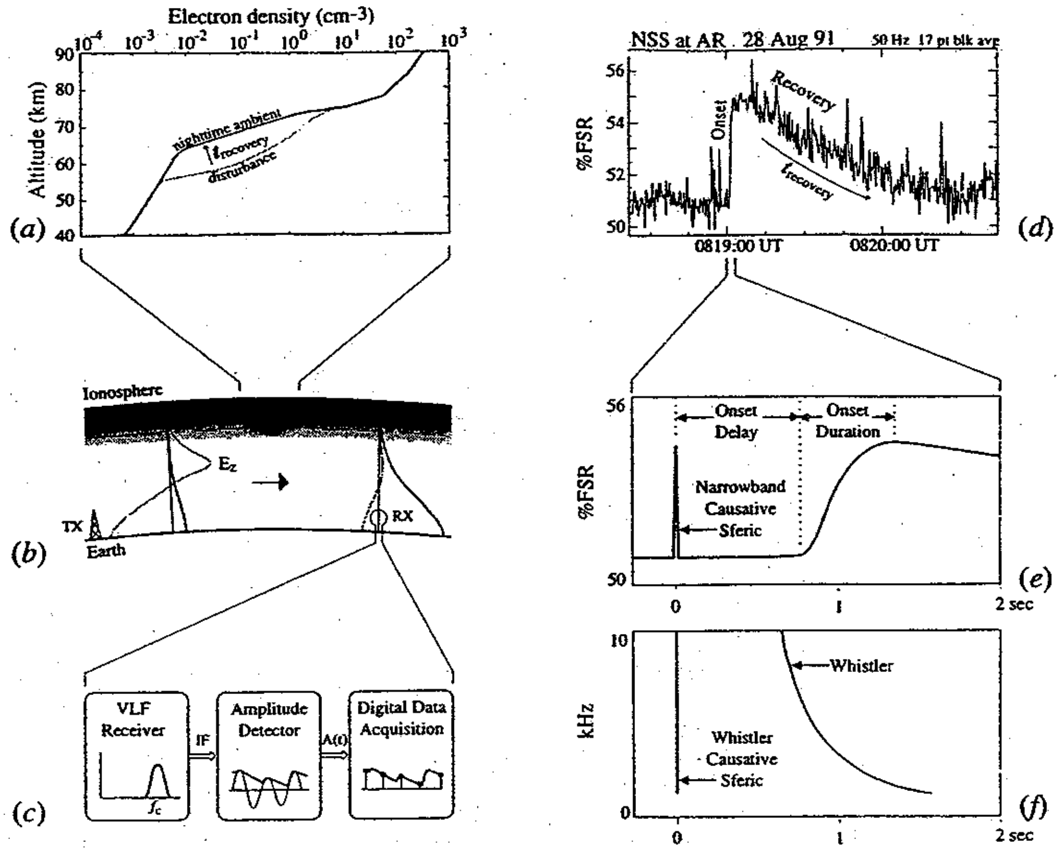

Fig.2. Remote sensing of transient ionospheric disturbances using subionospheric VLF radio. (*a*) Electron precipitation disturbs the ambient nighttime density profile of the ionosphere. The profile recovers to the ambient over about 1 min. (*b*) The disturbance changes the relative amplitudes and phases of the Earth-ionosphere waveguide modes which constitute a subionospheric VLF signal propagating nearby. The vertical electric field (E_z) components of two possible modes are illustrated. (*c*) The subionospheric signal is acquired with a narrow-band VLF receiver, whose intermediate frequency (IF) output is amplitude detected. The resulting signal amplitude $A(t)$ is sampled and recorded. (*d*) The signal amplitude perturbation caused by the ionospheric disturbance appears as an upgoing or downgoing onset followed by a roughly exponential recovery to the ambient signal level. When calibration is unavailable, signal amplitudes are given as a percent of the recording limit, or "full-scale range" (FSR), of the acquisition system. NSS is the transmitter, AR is the receiver (see the abbreviations in Tables 1 and 2). (*e*) The causative sferic (see Figure 1) is often strong enough to be detectable in the narrow-band record when the perturbation onset is examined closely and provides a time reference for comparison with the associated whistler (*f*). The sferics

in (*e*) and (*f*) are shown arriving at their respective receivers simultaneously, but the difference in propagation delay can be 40 ms or more when the narrow-band and broadband receivers are in opposite hemispheres [Figure from /9/].

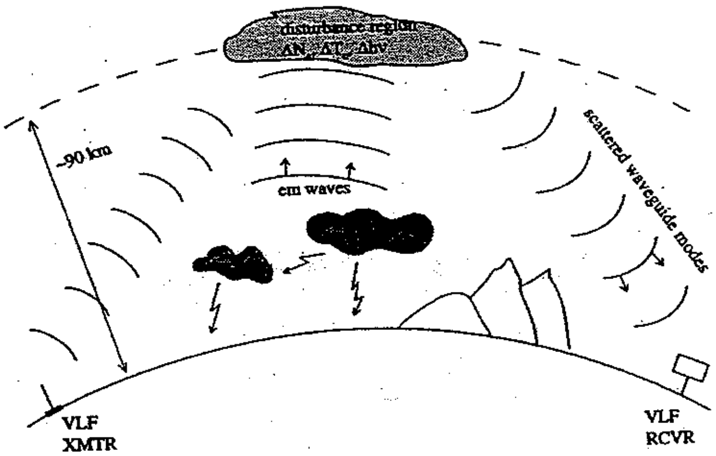

Fig. 3. EM radiation from lightning propagates upward, interacting with the lower ionosphere, heating the electrons and producing ionization changes. A subionospheric VLF signal propagating between a transmitter and a receiver on the earth's surface is used to measure the disturbance.

In this paper, we briefly review both of these fundamentally different processes by which lightning discharges affect the lower ionosphere, presenting samples of recent experimental and theoretical results.

LIGHTNING-INDUCED ELECTRON PRECIPITATION

The LEP process has been known for some time, as discussed above. However, the importance of this phenomena on a global scale has only recently emerged. Extensive observations in the northern and southern hemispheres indicate that this process regularly occurrs at mid-to-low latitudes /16,17/, with geomagnetically conjugate regions being disturbed simultaneously (within 1 s) in single lightning events /18/. Observations in South Africa and New Zealand indicate that LEP events occur at all longitudes and on L-shells as low as $L = 1.6$ /19,20/. Within the relatively dense plasmasphere, LEP events involve electrons with energies > 50 keV (and therefore produce disturbances at lower ionospheric altitudes of < 100 km) on L-shells of $L <\sim 3$ /21,22/. Outside the plasmasphere, where the resonant electron energies become higher due to the reduced cold plasma density, precipitation bursts typically occur due to VLF emissions triggered by whistlers /23/.

Subionospheric VLF signatures of LEP events are identified by means of their characteristic signatures, involving rapid (< 1 s) onsets followed by relatively slower (10-100 s) recoveries, as illustrated in Figure 4. The temporal relationship of the event onset to the causative lightning is established by comparison with detected time of occurrence of lightning, the associated radio atmospheric and/or the magnetospherically propagated whistler observed in the conjugate region.

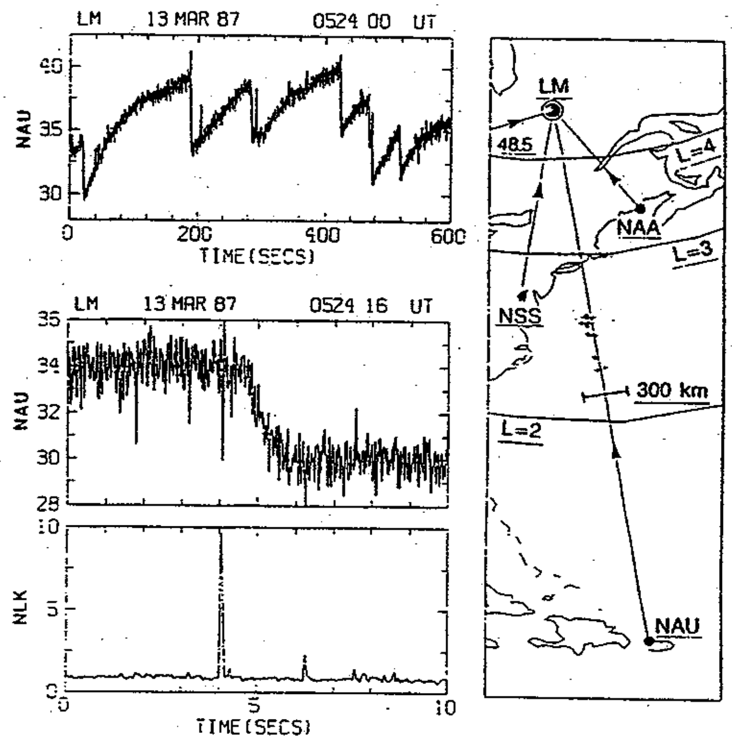

Fig. 4. Illustration of high resolution event signatures. Examples of perturbation events observed at LM on the 28.5 kHz NAU signal. The map on the right shows the propagation path as well as the location of cloud-to-ground lightning discharges (+'s) detected by the SUNY-Albany network /24/. The top panel shows a 10-minute sequence of successive events. The vertical axis shows signal intensity (A) in linear arbitrary units, with $A = 0$ representing the absence of signal. The signal intensity was time averaged over 320 ms. The middle panel shows high resolution display of the first event from the upper panel. The signal intensity is displayed with only 20 ms averaging. The bottom panel shows the intensity in the 24.8±0.15 kHz channel, used for spheric detection since the intensity of the signal from the NLK transmitter is relatively low. The data displayed in the bottom panel was time averaged over 50 ms. A causative spheric is clearly evident in the NLK channel. The UT shown in the upper right corner corresponds to $t = 0$ on the abcissa. The delay from the spheric to the event onset is ~ 0.7 s and the duration of onset (risetime) is ~ 1 s, consistent with that expected on the basis of gyroresonant whistler-particle interaction in the magnetosphere /21/.

Evidence for the simultaneous (within 1 s) disturbance of geomagnetically conjugate regions is illustrated in Figure 5. Analysis of available data indicates such disturbances commonly occur; however, the detailed timing between the northern and southern hemisphere perturbations vary from case to case /9/. In some cases, the northern region appears to be perturbed first (i.e., 0.1 – 0.2 s earlier than the south) in other cases the reverse is seen. Such variability is consistent with theoretical predictions, especially at longitudes in the vicinity of the South Atlantic Magnetic Anomaly, due to the difference between mirror altitudes at the two hemispheres /13,12/.

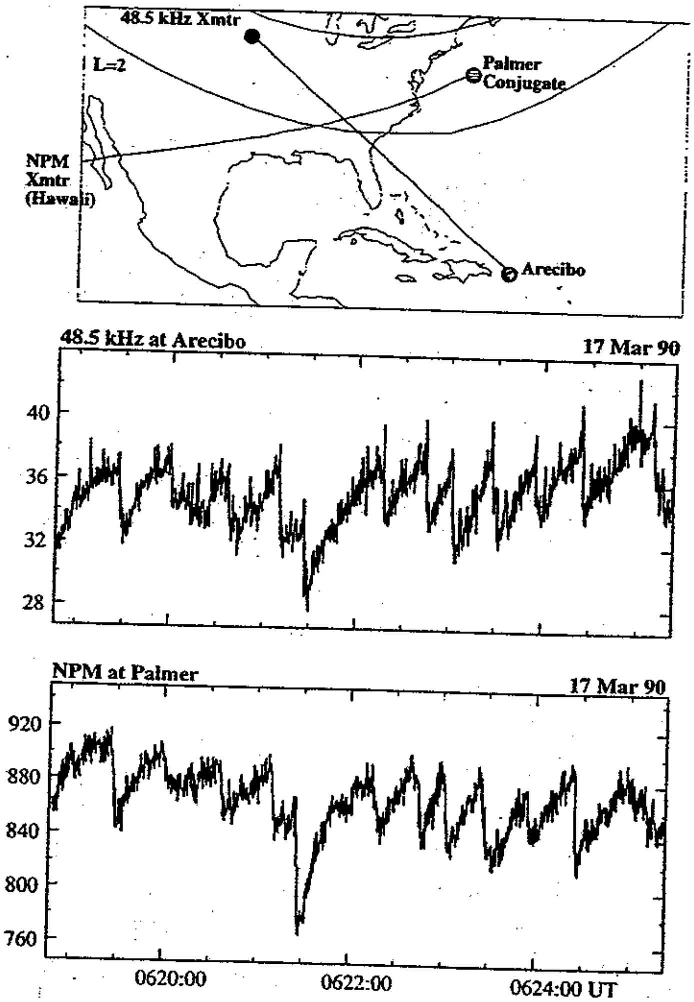

Fig. 5. Conjugate ionospheric perturbations observed on the 48.5 kHz signal at Arecibo (AR) (see map in top panel) and on the 23.4 kHz NPM signal originating in Hawaii and observed at Palmer Station, Antarctica (see map for the geomagnetic conjugate footprint of the NPM-Palmer

path). Analysis of perturbations on other paths (not shown) on this day indicate that the disturbed ionospheric region in the north was near the crossing of the 48.5-Arecibo path with the geomagnetic conjugate footprint of the NPM-Palmer path, shown in the top panel.

Recent data from Palmer Station, Antarctica indicated that ducted whistlers were not only observed in temporal association with VLF perturbation events in a manner fully consistent with an equatorial gyroresonant interaction being the causative agent, but also were found to be arriving from an azimuthal direction consistent with the whistler duct being located near the perturbed VLF signal path (NPM-Palmer) /9/. Studying in detail many such cases, /9/ concluded that *every* ducted whistler must be precipitating an electron burst *somewhere*, with the ionospheric effects of such bursts being detectable only when the disturbed region is within 100-200 km of an observed subionospheric VLF path. In this context, it is important to note that, for example at Palmer Station, Antarctica, *every* VLF perturbation event has always been found to be accompanied by a ducted whistler event, although typically many more whistlers are observed than VLF perturbations /25/. Simultaneous perturbation of widely spaced paths were not uncommon, suggesting either that many ionospheric regions or one large (> 1000 km in extent) region were disturbed in individual events /8/. However, further observations at multiple stations and over many criss-crossing VLF paths /16/ indicated that the disturbed ionospheric regions had transverse extents of order $\sim$ 100 km and had to in most cases be within 100-200 km of the affected paths, consistent also with theoretical modeling of VLF propagation in the earth-ionosphere waveguide /26,27/.

The data shown in Figures 6 and 7 illustrates the implications of the /9/ concept of *every* whistler causing a precipitation burst. In the case shown, perturbations are observed once again on the NPM-Palmer path as illustrated in Figure 6. However, the associated whistler event shown in Figure 7 for one of the events, is quite complex, being a composite of whistlers which have propagated on a multitude of ducts (estimates indicate > 5 ducts active at this time), with intense emissions triggered along at least some paths, indicating signal amplification and strong wave-particle interaction effects. The whistler component associated with the NPM-Palmer events is the first arriving traces, actually relatively weaker (probably because the duct exit point is at a distance from Palmer), but clearly arriving from a direction consistent with the duct being on the NPM-Palmer path. The other, stronger, whistler components are arriving from other directions, and estimates based on whistler dispersion indicates that the associated ducts are distributed over the range of $2.2 < L < 3.2$. Based on the /9/ hypothesis, we would expect precipitation bursts to be deposited at the ionospheric end points of all of the ducts involved, each of these regions being disturbed at least as strongly as the one which happened to be located near the NPM-Palmer path. If we had a much denser disturbution of VLF paths, we would have observed all of the paths being simultaneously excited in each of the whistler events.

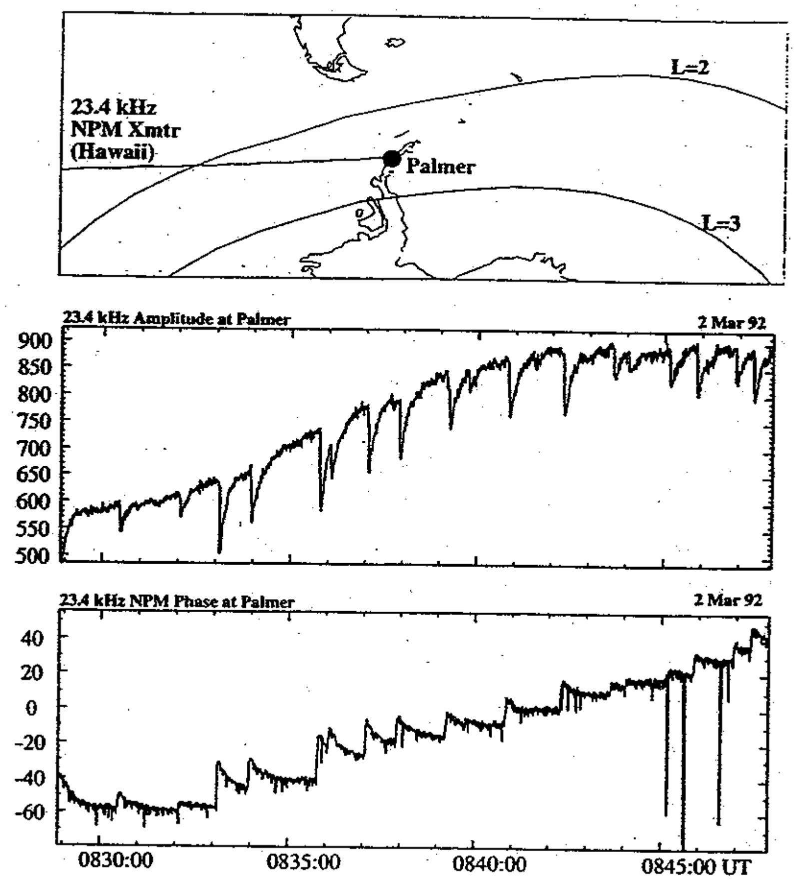

Fig. 6. A sequence of VLF perturbations observed at Palmer Station, Antarctica on the 23.4 kHz signal from the NPM transmitter in Hawaii. Both the amplitude and phase of the signal are perturbed repeatedly.

Carrying their hypothesis to its natural conclusion, /9/ estimated the lifetimes of 70-200 keV electrons assuming that every whistler observed at Palmer precipitates a burst of electrons. Their estimates indicate that the resulting lifetimes for the electrons in the $2 < L < 3$ range are comparable to the estimates of /28/, who considered losses due to plasmaspheric hiss and concluded that the structure of the belts in this range was controlled to first order by cyclotron resonant scattering by hiss. It thus appears that precipitation of electrons by *ducted whistlers* may well be an important, if not dominant, contributor to the belt loss rates on a global scale.

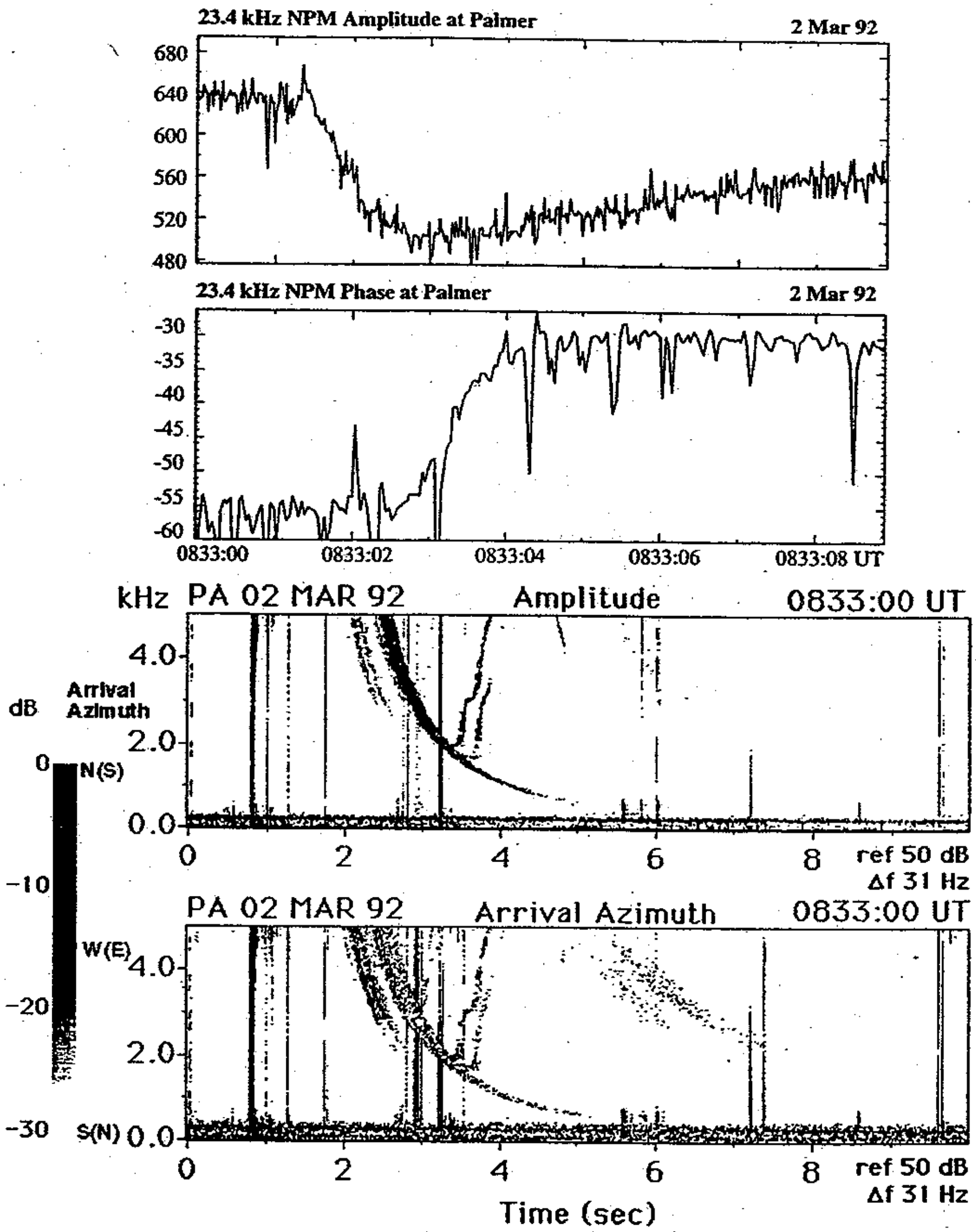

Fig. 7. Expanded records illustrating one of the events from Fig. 6. The lower panels show frequency time spectrograms illustrating the associated whistlers. The top sectrogram shows whistler

intensity whereas the lower ones show arrival direction. The relatively weak earlier components are arriving from a westward direction consistent with the NPM-Palmer path (see Figure 6).

LIGHTNING-INDUCED HEATING AND IONIZATION

The distinction between the temporal signatures of LEP events and lightning-induced heating events is illustrated in Figure 8, showing both types of events observed within a few minutes of one another on 25 January 1990. Analyzing the case shown in detail together with lightning location and intensity data, /14/ showed that the heating type VLF perturbations occurred in association with cloud-to-ground lightning discharges within < 50 km of the perturbed VLF paths, whereas the LEP events were observed in association with discharges that could be as much as 500 km distant from the disturbed paths. The latter is consistent with previous findings /29/, suggesting that the location of the ionospheric regions disturbed in LEP events is more strongly controlled by the availability of magnetospheric propagation paths (i.e., ducts) than lightning location itself.

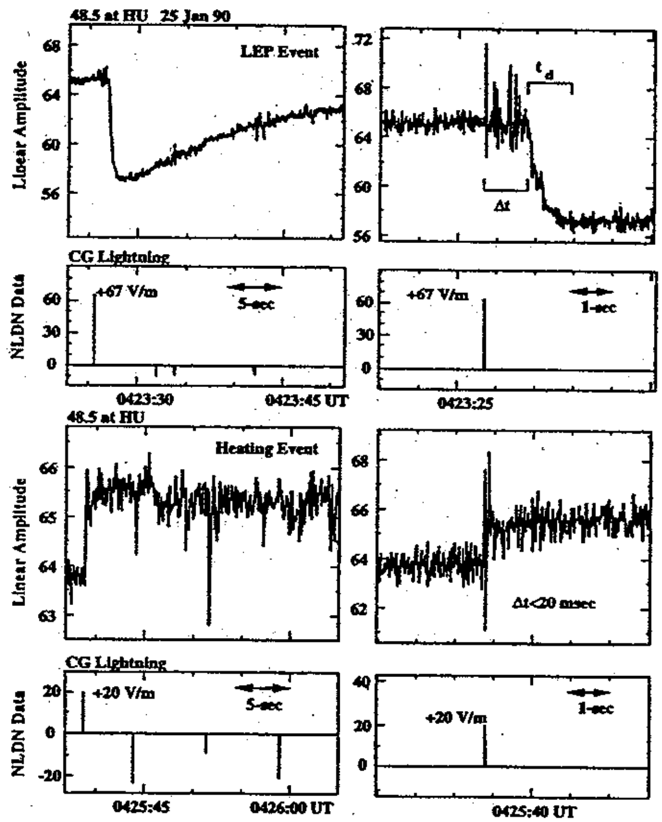

Fig. 8. Comparison of high-time-resolution signatures of LEP and heating events. Right hand panels show 20 ms data samples with no averaging, whereas left hand panels show the same data time

averaged over 80 ms. The vertical axes show linear amplitude as in Figure 3. For the heating type events, any onset delay Δt and duration t_d is estimated to be less than the measurement resolution of 20 ms.

An example of a sequence of *early* VLF perturbations are illustrated in Figure 9. Once again, the expanded records in the lower panel clearly show that the event onsets are simultaneous (within measurement resolution of 10 ms) with the radio atmospherics from lightning. Although the case shown has not yet been analyzed in detail, the data is consistent with previously reported examples of such events. The disturbance of the NAU-Gander path in this case probably occurs due to a storm center located off the east coast of the United States, somewhere near (most likely within 50 km) of the NAU-Gander path.

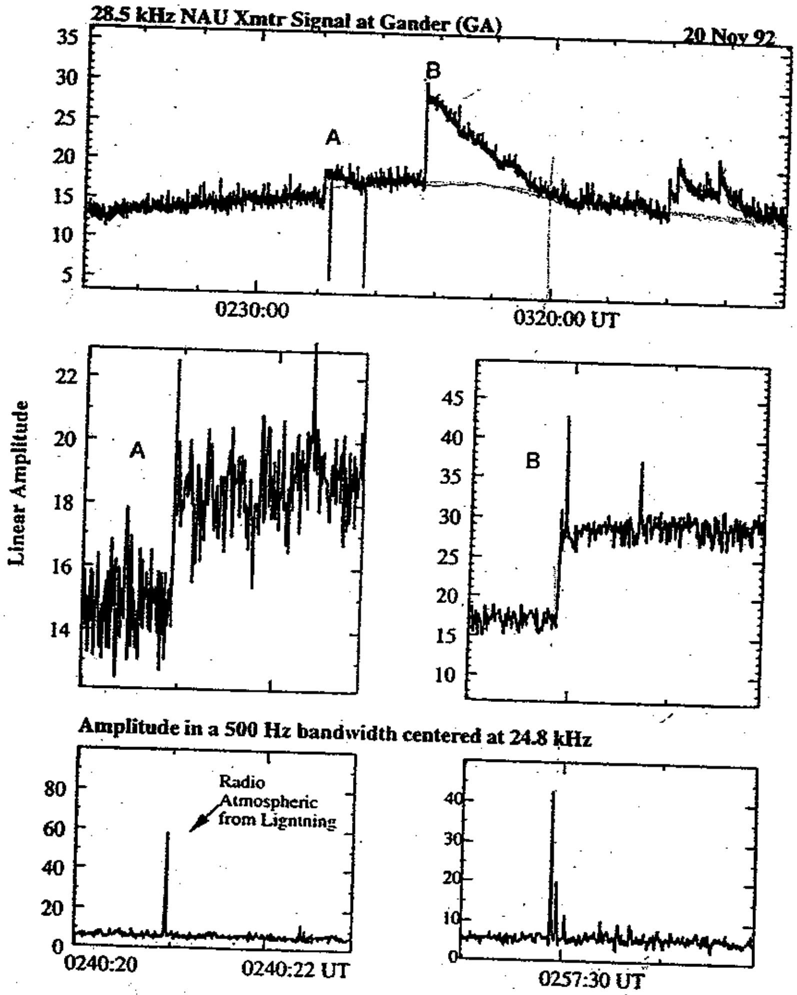

Fig. 9. A sequence of a lightning-induced ionospheric heating events detected at Gander, New-

foundland on the 28.5 kHz signal from the NAU transmitter in Puerto Rico arriving over a path as shown. The top panel shows the amplitude of the NAU signal exhibiting sudden amplitude changes followed by relatively slow (>100 s) return to pre-event levels. The bottom panels show expanded records of two events marked A and B, together with the radio atmospherics generated by the lightning, which determine the time of origin of the event. The delay between the lightning and the signal amplitude change (and therefore the ionospheric disturbance) is less than 10 ms (measurement resolution) .

Events such as the ones shown in Figure 9 are believed to result from enhanced secondary ionization produced at 80-100 km altitudes, due to the intense heating of ionospheric electrons by the electromagnetic impulse from lightning /6/. A fully kinetic and self consistent model of the interaction of intense EM pulses from lightning with the lower ionosphere /30/ indicates that ionization produced by individual EM pulses would be significant, as illustrated in Figure 10. Under nighttime conditions, individual lightning EM pulses of 10-20 V/m (normalized to 100-km free space distance) produce changes in electron density of 1-30% of the ambient whisle a sequence of such pulses leads to more than 100% modification at altitudes between 85 to 92 km /30,31/. It thus appears that 'bubbles' of enhanced ionization are produced in the nighttime D-region above active thunderstorm regions, as first predicted by /6/. Although our present kinetic model of the interaction is only one dimensional, previous estimates based on simpler models of the coupling indicate that the transverse size of the heated regions is of order few hundred kilometers at 85 km altitude, with the region of enhanced ionization being smaller, of order 50-100 km in extent /32/.

A very interesting aspect of the ionospheric disturbances is the fact that attachment processes dominate at altitudes below $\sim$ 85 km, leading to reduction in density whereas ionization dominates at higher altitdes. As a result, the nighttime D-region density profile is effectively sharpened, with the scale height decreasing by a factor of $\sim$ 2 /31/.

SUMMARY

Both experimental evidence and theoretical modeling indicate that electromagnetic energy released in lightning discharges commonly produces significant and easily detectable disturbances in the nighttime lower ionosphere. In the case of lightning-induced electron precipitation, the source of the energy leading to the disturbances is that which is resident in the trapped electrons of the earth's radiation belts, the available momenta of which are re-directed in gyroresonant interactions with relatively weak whistler waves from lightning. In the case of lightning-induced heating and ionization, the source of the energy is the intense EM radiation itself, substantially heating the otherwise cold electrons of the nighttime D region. IN view of the omnipresence of lightning across our planet, the global significance of both of these processes needs to be further investigated, both theoretically and with carefully designed experiments.

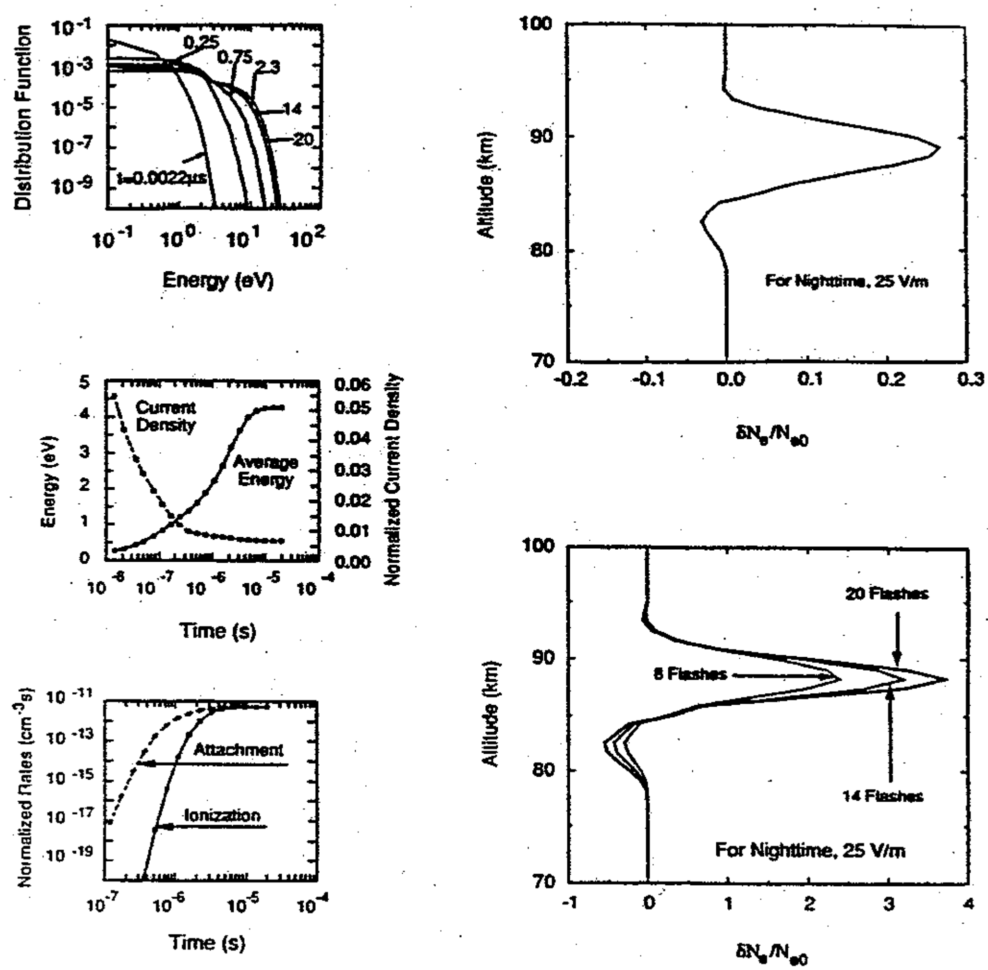

Fig. 10. Enhanced ionization and attachment resulting from lightning-induced heating of the nighttime lower ionosphere, taken from /30/, and calculated using a fully kinetic and time-dependent solution of the Boltzmann transport equation with all losses included and taking account of the time evolution of the electron distribution function. On the left: (a) Time evolution of the electron distribution function at 90 km altitude under the influence of a 10 V/m constant electric field being applied at time $t = 0$. Curve 1 is for 0.022 μs, 2 for 0.25 μs, 3 for 0.75 μs, 4 for 2.25 μs, 5 for 14 μs, and 6 for 20 μs. (b) Time evolution of the normalized electric current and average electron energy. (c) Time evolution of the attachment and ionization rates. Upper right: The resulting density changes for a single EM pulse with 25 V/m initial (at 70 km altitude) amplitude for the nighttime conditions. Lower right: The resulting density changes for 8, 14, and 20 succesive EM pulses with 25 V/m initial (at 70 km altitude) amplitude for the nighttime conditions [Figures from /30/].

REFERENCES

1. J.A.Cambers, *Atmospheric Electricity*, p. 307, Pergamon, London, 1967.

2. E.P.Krider and C.Guo, The peak electromagnetic power radiated by lightning return strokes, *J. Geophys. Res.*, *88*, 8471, (1983).

3. J.W.Dungey, Loss of Van Allen electrons due to whistlers, *Planetary Space Sci.*, *11*, 591, (1963).

4. C.T.R.Wilson, The electric field of a thundercloud and some of its effect, *Proc. Phys. Soc. London*, *37*, 32D, (1925).

5. D.K.Bailey, and D.F.Martin, The influence of electric waves on the ionosphere, *Phil. Mag. S.7*, *18*, 369, (1934).

6. U.S.Inan, T.F.Bell, and J.V.Rodriguez, Heating and ionization of the lower ionosphere by lightning, *Geophys. Res. Lett.*, *18*, 705, (1991).

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

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

9. W.C.Burgess, and U.S.Inan, The role of ducted whistlers in the precipitation loss and equilibrium flux of radiation belt electrons, *J. Geophys. Res.*, *98*, No. A9, 15,643, (1993).

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

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

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

13. U.S.Inan, 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*b*).

14. U.S.Inan, J.V.Rodriguez, and V.P.Idone, VLF signatures of lightning-induced heating and ionization of the nighttime D-region, *Geophys. Res. Lett*, in press, (1993).

15. U.S.Inan, VLF heating of the lower ionosphere, *Geophys. Res. Lett.*, *17*, 729, (1990).

16. U.S.Inan, F.A.Knifsend, and J.Oh, Subionospheric VLF "Imaging" of lightning-induced electron precipitation from the magnetosphere, *J. Geophys. Res.*, *95*, 17217, (1990).

17. A.J.Smith and P.D.Cotton, The trimpi effect in Antarctica: Observations and models, *J. Atmos. Terr. Phys.*, *52*, 341, (1990).

18. W.C.Burgess and U.S. Inan, Simultaneous disturbance of conjugate ionospheric regions in association with individual lightning flashes, *Geophys. Res. Lett.*, *17*, 259, (1990).

19. R.L.Dowden, and C.D.D.Adams, Phase and amplitude perturbations on the NWC signal at Dunedin from lightning-induced electron precipitation, *J. Geophys. Res.*, *94*, 497, (1989*a*).

20. R.H.W.Friedel and A.R.W.Hughes, Trimpi events on low latitude paths: an investigation of gyroresonance interactions at low *L*-values, *J. of Atmos. and Terr. Phys.*, *54*, No. 10, 1375, (1992).

21. H.C.Chang and U.S.Inan, Lightning-induced electron precipitation from the magnetosphere, *J. Geophys. Res.*, *90*, 1531, (1985*a*).

22. D.L.Carpenter and U.S.Inan, Seasonal, Latitudinal and Diurnal distribuiton of whistler-induced precipitation events at low latitudes, *J. Geophys. Res.*, *92*, 3429, (1987).

23. B.Dingle and D.L.Carpenter, Electron precipitation induced by VLF noise bursts at the plasmapause and detected at conjugate ground stations, *J. Geophys. Res.*, *86*, 4597, (1981).

24. U.S.Inan, W.C.Burgess, T.G.Wolf, D.C.Shafer, and R.E.Orville, Lightning-associated precipitation of MeV electrons from the inner radiation belt, *Geophys. Res. Lett.* *15*, 172, (1988*a*).

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

26. W.L.Poulsen, T.F.Bell, and U.S.Inan, Three-dimensional modeling of subionospheric VLF propagation in the presence of localized *D* region perturbations associated with lightning, *J. Geophys. Res.*, *95*, 2355, (1990).

27. W.L.Poulsen, T.F.Bell, and U.S.Inan, The scattering of VLF waves by localized ionospheric disturbances produced by lightning-induced electron precipitation, *J. Geophys. Res.*, *98*, 15,553-15,559, (1993*b*).

28. L.R.Lyons, and R.M.Thorne, Equilibrium structure of radiation belt electrons, *J. Geophys. Res.*, *78*, 2142, (1973).

29. W.-Y.Yip and U.S.Inan, On the spatial relationship between lightning discharges and propagation paths of perturbed subionospheric VLF/LF signals, *J. Geophys. Res.*, *96*, 249, (1991).

30. Y.N.Taranenko, U.S.Inan and T.F.Bell, Interaction with the lower ionosphere of electromagnetic pulses from lightning: heating, attachment, and ionization, *Geophys. Res. Lett.*, *20*, 1539, (1993).

31. Y.N.Taranenko, Interaction with the lower ionosphere of electromagnetic pulses from lihgtning: heating, attachment, ionization, and optical emissions, *PhD Thesis*, Stanford University, September 1993.

32. J.V.Rodriguez, U.S.Inan, Y.Q.Li, R.H.Holzworth, A.J.Smith, R.E.Orville, and T.J.Rosenberg, A case study of lightning, whistlers, and associated ionospheric effects during a substorm particle injection event, *J. Geophys. Res.*, *97*, 65-75, (1992*a*).