JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 97, NO. A1, PAGES 65–75, JANUARY 1, 1992

A Case Study of Lightning, Whistlers, and Associated Ionospheric Effects During a Substorm Particle Injection Event

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Simultaneous ground-based observations of narrowband and broadband VLF radio waves and of cloud-to-ground lightning were made at widely spaced locations during the 1987 Wave-Induced Particle Precipitation (WIPP) campaign, conducted from Wallops Island, Virginia. Based on these observations, the first case study has been made of the relationships among located cloud-to-ground (CG) lightning flashes, whistlers, and associated ionospheric effects during a substorm particle injection event. This event took place 2 days after the strongest geomagnetic storm of 1987, during a reintensification in geomagnetic activity ($Kp = 5$) that did not affect the high rate of whistlers observed at Faraday Station, Antarctica ($L = 2.46$). At the time of the injection event, several intense nighttime thunderstorms were located over Long Island and the coast of New England, between 400 km northwest and 600 km north of the region geomagnetically conjugate to Faraday. About two thirds of the CG flashes that were detected in these thunderstorms during the hour following the injection event onset were found to be causatively associated with whistlers received at Faraday. During the same period the amplitude of the 24.0-kHz signal from the NAA transmitter in Cutler, Maine, propagating over the thunderstorm centers toward Wallops Island was repeatedly perturbed in a manner characteristic of previously reported VLF signatures of transient and localized ionization enhancements at D region altitudes. Though such enhancements may have been caused by whistler-induced burst electron precipitation from the magnetosphere, the data in this case are insufficient to establish a clear connection between the NAA amplitude perturbations and the Faraday Station whistlers. In view of the proximity of the NAA great circle path to the storm center, heating of the lower ionosphere by intense radiation from lightning may also have played a role in the observed VLF perturbations. The onset of each of the NAA signal perturbation events coincided with an intense cluster of radio atmospherics. Detailed temporal variations in the ELF (0.3-3 kHz) and VLF (3-30 kHz) power of similar "sferic clusters" correlated well with variations in the power of simultaneous "anomalous" optical events (AOEs) observed by a down-looking photodiode detector on a rocket at altitudes between 150 and 412 km.

1. INTRODUCTION

Lightning is a frequent and powerful source of electromagnetic radiation that can couple the neutral atmosphere, the ionosphere, and the magnetosphere. At ELF (0.3-3 kHz) and VLF (3-30 kHz) frequencies, such radiation propagates in the magnetosphere in the whistler mode [*Helliwell*, 1965]. Interactions in the magnetosphere between whistler mode waves and electrons are a form of coupling between atmospheric regions that is well documented but still not completely understood. The whistler mode wave can exchange energy through gyroresonant interactions with trapped energetic electrons at or near the geomagnetic equator, lowering the mirror height of some of the electrons and causing them to precipitate into the atmosphere, either directly in the hemisphere in which the wave originated or in the conjugate hemisphere following mirroring or backscattering from the top of the neutral atmosphere [*Chang and Inan*, 1985]. Bursts of precipitating electrons associated with whistlers have been measured in situ by rockets [*Rycroft*, 1973; *Goldberg et al.*, 1986] and satellites [e.g., *Voss et al.*, 1984]. Precipitation due to whistler-triggered emissions propagating outside the plasmapause has been detected as secondary bremsstrahlung X rays and optical emissions [*Rosenberg et al.*, 1971; *Bering et al.*, 1980; *Helliwell et al.*, 1980; *Doolittle and Carpenter*, 1983].

Secondary ionization due to whistler-induced burst electron precipitation has been causatively associated with characteristic amplitude and phase perturbations of VLF, LF, MF, and HF radio signals propagating in the Earth-ionosphere waveguide [*Baum*, 1963; *Helliwell et al.*, 1973; *Carpenter et al.*, 1984; *Moser et al.*, 1988]. The secondary ionization causes a localized increase in the ionization density at D region altitudes that, analogous to a dent in a metallic waveguide, perturbs the mode structure of the propagating wave. The ensuing constructive or destructive interference between the modes causes a temporary perturbation of the amplitude and/or phase of the signal that is often referred to as a "Trimpi" event [*Wolf and Inan*, 1990]. The delay between the causative radio atmospheric and the "Trimpi" event onset ("onset delay") typically is less than 1 s [*Inan and Carpenter*, 1986], the onset duration typically is less than 2 s, and the recovery lasts about 10-100 s [*Carpenter et al.*, 1984]. (A "radio atmospheric" or "sferic" is the electromagnetic impulse from a discharge in the atmosphere, such as a return stroke in a cloud-to-ground (CG) lightning flash.)

Some VLF amplitude perturbations have been observed with onset delays and/or onset durations of <50 ms, too short to be attributed to whistler-induced burst electron precipitation, although the magnitude and recovery time of the perturbation are consistent with a localized increase in the ionization density at D region altitudes as described above [*Armstrong*, 1983; *Inan et al.*, 1988*a*, *b*]. Such events are thus considered "early" and/or "fast" with respect

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Paper number 91JA02583.
0148-0227/92/91JA-02583$05.00

to perturbations caused by burst electron precipitation. The very short onset delays and/or onset durations suggest that CG lightning or other discharge energy may somehow be coupling nearly immediately and directly upward to the D region and creating the ionization enhancements [*Armstrong*, 1983; *Inan et al.*, 1988*a*, *b*]. Following the observation of localized heating of the nighttime D region by signals from a VLF transmitter [*Inan*, 1990], heating and ionization of the lower ionosphere by radio frequency radiation from lightning have been suggested as one form of direct coupling that could account for the observed "early" and/or "fast" VLF perturbations [*Inan et al.*, 1991].

This paper presents the first case study of CG lightning, sferics, whistlers, VLF amplitude perturbations, and other ionospheric phenomena during a substorm particle injection event. We find that the relationships among these phenomena may be more complex than earlier studies have indicated. Most previous work has focused on detailed analyses of data sets characterized by relatively modest whistler and lightning activity. These include separate studies of connections between lightning and whistlers [*Carpenter and Orville*, 1989]; whistlers and "Trimpi" events [*Inan and Carpenter*, 1986]; CG lightning and VLF perturbation events [*Inan et al.*, 1988*a*]; and sferics and VLF perturbation events [*Inan et al.*, 1988*b*]. In the present study, however, the relationships among these phenomena, except for the connection between CG lightning and whistlers, have turned out to be harder to clarify, possibly due in part to the high lightning and whistler rates. In spite of this we propose that the ionospheric phenomena considered in this case study may represent new evidence of direct coupling of lightning energy to the lower ionosphere, either in conjunction with or in the absence of gyroresonant interactions in the magnetosphere between whistler mode waves and electrons.

2. Description of the Experiment

The data analyzed for this paper were acquired in the course of the Wave-Induced Particle Precipitation (WIPP) campaign, conducted between July 10 and August 1, 1987, from Wallops Island, Virginia, in order to investigate, through coordinated ground-, balloon-, and rocket-based experiments, the causes and effects of particle precipitation induced by natural and man-made electromagnetic waves. Nighttime radio wave measurements were made at the ground stations listed in Table 1. Broadband ELF and VLF data were recorded for the purpose of investigating the spectral signatures of whistlers, emissions, and sferics, while narrowband (±150 Hz) recordings of signals from one LF and several VLF transmitters, indicated in Table 2, were used to monitor a "network" of subionospheric VLF signals for VLF perturbation events. A map of part of this "network" is shown in Figure 1; the locations of three ground stations (WI, LM, GN) and two transmitters (NAA, NSS) are shown on this map. (A similar network configuration was used in more recent work to locate ionospheric disturbances due to burst electron precipitation [*Inan et al.*, 1990].) The Lightning Detection Network operated by the State University of New York at Albany (SUNYA) [*Orville et al.*, 1983] automatically located CG lightning flashes in the eastern United States. Riometers at Wallops Island and at Lake Mistissini, Quebec, were used to measure ionospheric absorption of galactic VHF noise as another means of detecting ionization enhancements due to electron precipitation.

TABLE 1. WIPP Campaign Ground Stations

Station	Code	L shell	Latitude	Longitude
Stanford, Calif.	SU	1.89	37.4°N	122.2°W
Faraday Station, Antarctica	FA	2.46	65.2°S	64.3°W
Wallops Island, Va.	WI	2.44	37.8°N	75.6°W
Grafton, N. H.	GN	3.26	43.6°N	71.9°W
Lake Mistissini, Quebec	LM	7.27	50.4°N	74.9°W

L shell values calculated for $Kp = 5$ using the model of *Tsyganenko* [1989].

TABLE 2. VLF/LF Transmitters

Call Sign	Transmitter	Frequency, kHz	Latitude, °N	Longitude, °W
NSS	USN Maryland	21.4	39.0	76.5
NPM	USN Hawaii	23.4	21.4	158.2
NAA	USN Maine	24.0	44.7	67.3
NLK	USN Washington	24.8	48.2	121.9
NAU	USN Puerto Rico	28.5	18.2	67.2
	USAF Nebraska	48.5	41.5	97.6

The SUNYA network and the transmitter signals received at Wallops Island (Table 2) were monitored during the campaign for the occurrence of lightning and VLF perturbation events. Evidence of such activity was a criterion for launching balloons and rockets. Several balloons carrying optical and electric field sensors were launched from Wallops Island during the last week of the campaign [*Li et al.*, 1991]. One of these balloons was aloft on July 31, 1987, when a sounding rocket was launched during the most intense phase of the second of two substorm particle injection events. *Hu et al.* [1989] reported stratospheric conductivity variations measured over a small thunderstorm during this balloon flight. The sounding rocket was equipped with optical sensors, electric field antennas, a magnetometer, and charged-particle detectors [*Arnoldy and Kintner*, 1989; *Massey et al.*, 1990; *Li et al.*, 1991].

3. Observations

Geomagnetic Activity

Starting with a sudden commencement on July 28, 1987, geomagnetic conditions were disturbed for several days leading up to the period of this case study. The highest Kp indices for 1987 were recorded on July 29 ($Kp_{max} = 7$; $\Sigma Kp = 34$). There was a reintensification of geomagnetic activity after 2300 UT on July 30. Two substorm particle injection events were subsequently observed on the geosynchronous GOES 7 satellite magnetometer (74.2°W; $L = 6.6$) at 0250 UT and at 0318 UT on July 31. The Kp index was 5 for the period 0300-0600 UT. Energetic particle fluxes from the injection events were detected on the satellite and reached their maximum level around 0400 UT [*Arnoldy and Kintner*, 1989].

The substorm particle injection event that began at 0318 UT was observed on the GOES 7 satellite as an enhancement of the flux of >2-MeV electrons and 0.6- to 4.2-MeV ions that lasted until 0500 UT [*Arnoldy and Kintner*, 1989]. Following the onset of the injection event, the 51.4-MHz riometer at Lake Mistissini, on nearly the same meridian as the GOES satellite, measured 1.5 dB maximum enhanced absorption followed by a quasi-periodic variation in the absorption consisting of three or four cycles, each 10-15 min long (Figure 2*d*). A similar quasi-periodic disturbance also appeared in the Lake Mistissini magnetometer data, superimposed on negative bay activity that reached a maximum excursion of $\Delta H = -600$ nT around 0330 UT (Figures 2*a*-2*c*). Magnetometer data from Faraday showed similar variations at this time. The absorption event and the main part of the magnetic disturbance appear to have ended by 0355-0400 UT, though the bay activity continued until about 0500 UT. However, the 30.0-MHz riometer at Wallops Island (Figure 2*e*) did not measure any noticeable absorption due to the injection event, consistent with latitude-chain riometer data, which reveal very few instances of absorp-

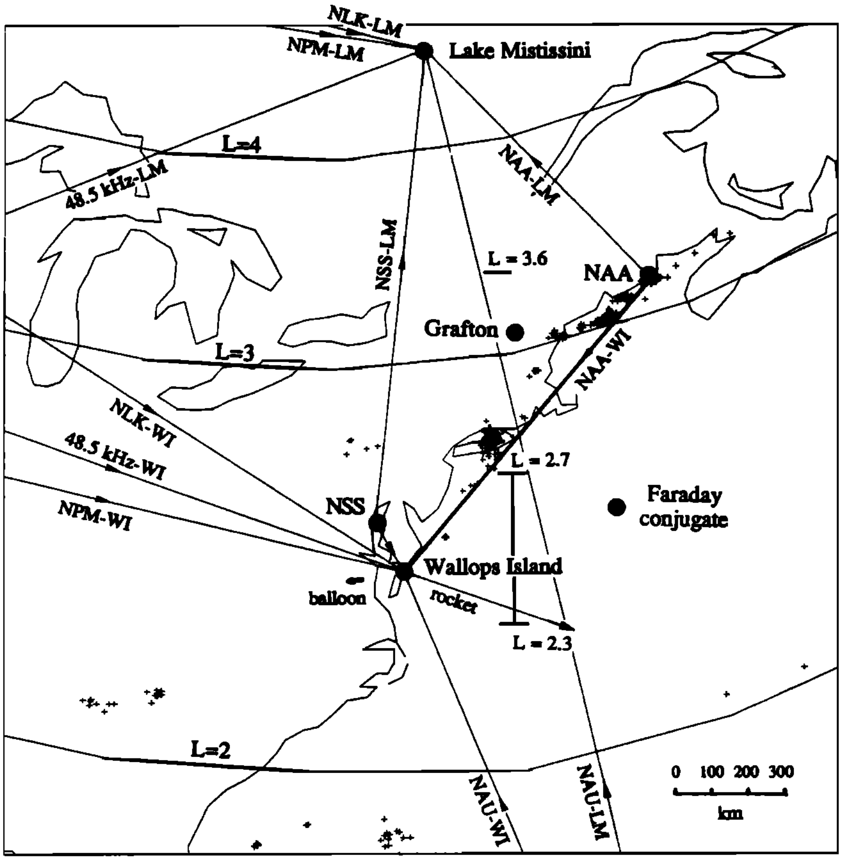

Fig. 1. Region monitored by WIPP campaign experiments on July 31, 1987. The pluses indicate cloud-to-ground lightning flashes located by the SUNYA Lightning Detection Network during the period 0350-0405 UT, July 31, 1987; the thunderstorms were essentially stationary during the hour 0330-0430 UT. Also indicated are the locations of the ground stations Wallops Island, Virginia; Lake Mistissini, Quebec; and Grafton, New Hampshire, as well as the geomagnetic conjugate location of Faraday Station, Antarctica. The loci of the $L = 2$, 3, and 4 (undisturbed) field lines at 100 km altitude are shown for reference, and the L shell ranges of whistler propagation as determined from measurements made at these stations ($L = 2.3$ to 2.7; $L = 3.6$) are indicated. The great circle subionospheric paths of VLF signals received at Wallops Island and Lake Mistissini from the transmitters in Table 2 are drawn on the map, as are the locations of the NAA and NSS transmitters. The NAA-to-Wallops Island (NAA-WI) great circle path is emphasized. The sounding rocket trajectory and the location of the balloon during the rocket flight are shown.

tion occurring over an L range as wide as 3.0-4.5 [*Lanzerotti and Rosenberg*, 1983]. Nevertheless, Pc 2-3 resonant micropulsations presumably due to the July 31 substorm injection were detected at Wallops Island (R. Arnoldy, private communication, 1990).

ELF-VLF Chorus

The signal strength of ELF-VLF chorus at Lake Mistissini rose sharply between 0356 and 0400 UT, as the riometer absorption event was ending and the particle fluxes from the second injection event observed on the GOES 7 magnetometer were reaching their peak. The magnitude of the increase can be appreciated by comparing spectra of Lake Mistissini broadband data from the minutes 0355 (Figure 3*a*) and 0410 (Figure 3*b*). Whereas the chorus (just barely audible, as recorded) cannot be seen in the earlier dynamic spectrum, it is visible above 1.7 kHz in the later dynamic spectrum. It increased in intensity until 0415 UT, then gradually decayed until, after 0501 UT, it was inaudible above the essentially constant level of sferic noise. Though ELF-VLF chorus was audible at Lake Mistissini, Faraday, and at Grafton, New Hampshire, on July 29 after the onset of the geomagnetic storm, chorus was inaudible at Faraday and very faint at Grafton during the most intense phase of the Lake Mistissini chorus on July 31. Since ELF-VLF chorus is believed to occur primarily on field lines in the low-density region outside the plasmapause [*Burtis and Helliwell*, 1976], it is likely that the plasmapause had recovered to a point poleward of Grafton ($L > 3.3$) by July 31. The large increase in the intensity of chorus activity at Lake Mistissini toward the end of the magnetic disturbance is consistent with previous observations [*Tokuda*, 1962].

Thunderstorms

A cold weather front moved southward through New England and New York on July 30, 1987, causing thunderstorms that at the time of the injection event (around local midnight) were lined up along the Atlantic coast [*National Oceanic and Atmospheric Administration*, 1987]. During the hour 0330-0430 UT the SUNYA Lightning Detection Network detected about 26 CG flashes per minute originating in these storms, which were located between Long Island and eastern Maine along the 1000-km great circle path of the 24.0-kHz NAA transmitter signal received at Wallops Island, Virginia (NAA-WI, Figure 1).

Whistlers

On July 31, 1987, the nighttime ELF-VLF radio spectrum at Faraday station was characterized by a high level of whistler activity. The whistler rate was about 60 per minute and was not

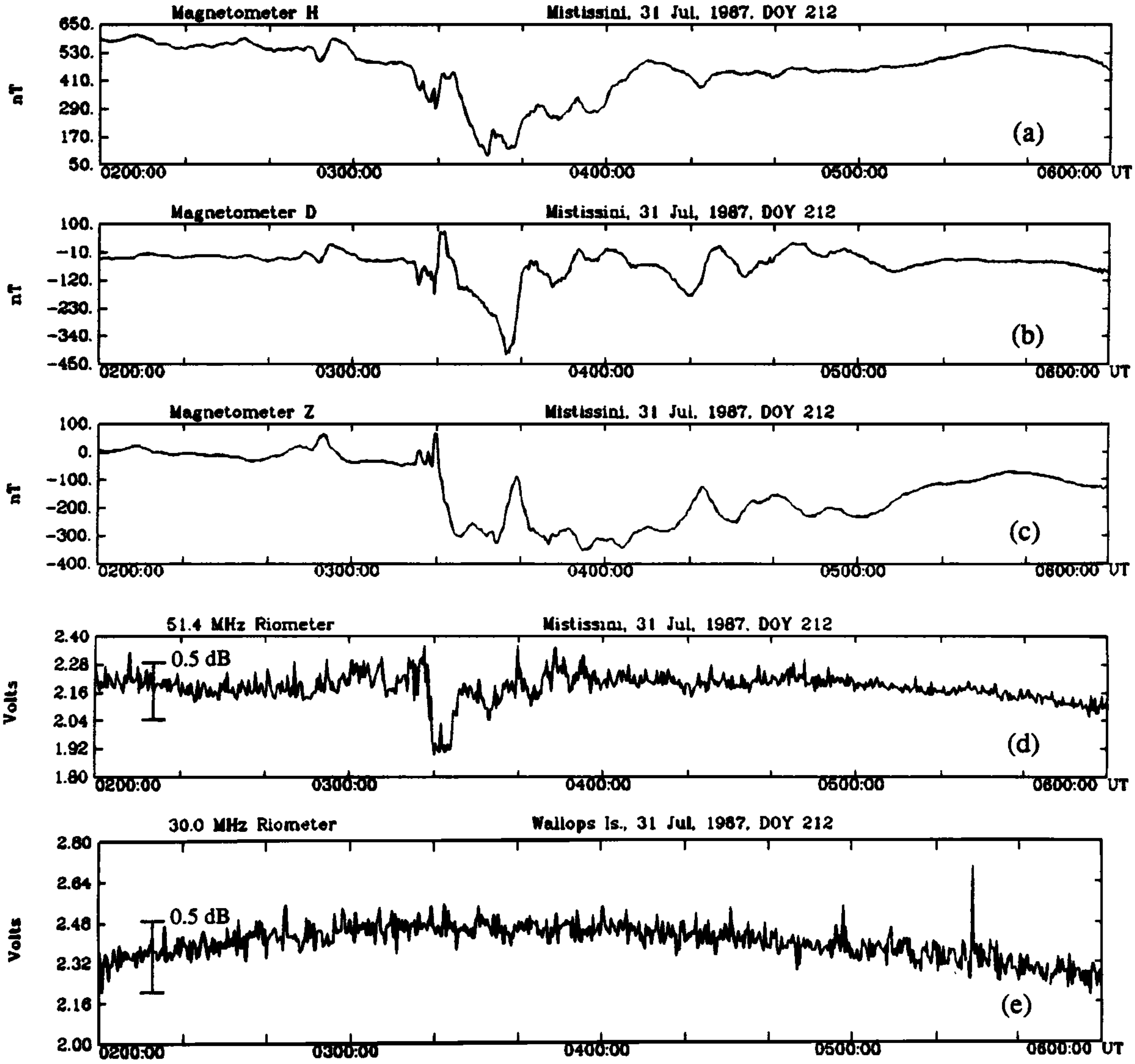

Fig. 2. Magnetometer data from Lake Mistissini and riometer data from Lake Mistissini and Wallops Island, 0200-0600 UT, July 31, 1987, showing effects of substorm particle injection events commencing at 0250 and 0318 UT. $Kp = 5$ for 0300-0600 UT. In a riometer the voltage output is proportional to the power received.

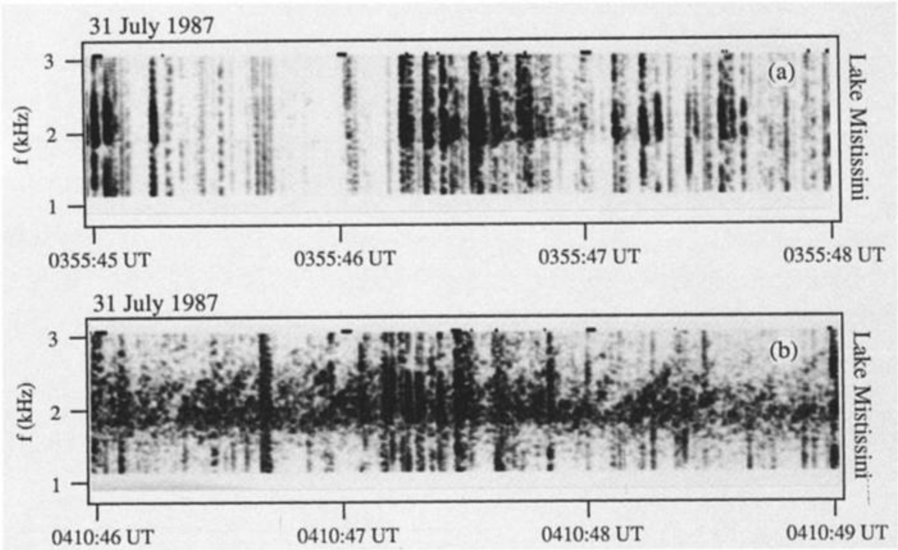

Fig. 3. Dynamic spectra (1- to 3-kHz) of broadband data from Lake Mistissini, July 31, 1987, for (*a*) 0355:45-0355:48 UT and (*b*) 0410:46-0410:49 UT. ELF-VLF chorus activity greatly increased in intensity between 0356 and 0400 UT. The dynamic spectra are shown for the same period as those in Figures 8 and 9.

noticeably affected by the substorm injection events at 0250 and 0318 UT. This rate and its insensitivity to geomagnetic disturbances are consistent with long-term observations made at Port Lockroy, Antarctica (64.8° S, 63.5° W), near the site of Faraday [*Laaspere et al.*, 1963]. Analysis of the Faraday whistlers from the period 0330-0430 UT on July 31 using the nose-frequency extrapolation methods of *Bernard* [1973] and *Park* [1972] indicates a dominant path of propagation at $L = 2.5 \pm 0.2$ and an equatorial electron density $N_{eq} = 600 \pm 200$ el cm^{-3}. Whistler echoing was rare during this period, with only a few, weak two-hop and a somewhat larger number of three-hop whistlers observed at Wallops Island and Faraday, respectively.

Occasionally (about twice per minute), a sferic excited a $L \simeq 2.5$ whistler and another whistler observed at Faraday with a delay consistently about twice that of the first. The second of the two whistlers was generally weaker and less well defined. Analysis of a relatively well defined single-source whistler event, with the two- and three-hop $L \simeq 2.5$ whistlers visible in the Wallops Island and Faraday dynamic spectra, respectively (Figure 4), shows that the second whistler was probably a one-hop whistler that propagated at a higher L shell, rather than a two-hop whistler that propagated in the Earth-ionosphere waveguide from Wallops Island back to Faraday. Nose-frequency extrapolation analysis of this whistler indicates propagation at $L \simeq 3.6$ and an equatorial electron density $N_{eq} \simeq 440$ el cm^{-3}. The delays between the causative sferics and the $L \simeq 3.6$ whistlers and the intensities of these whistlers decreased somewhat after 0330 UT. Two-, four-, and even six-hop whistlers propagating at $L \simeq 3.6$ were observed at Grafton starting about 2 hours after the onset of the particle injection event on July 31, but the data are insufficient to determine whether these were propagating in the same ducts as the $L \simeq 3.6$ whistlers observed earlier at Faraday.

VLF Perturbation Events Observed on the NAA-WI Signal

During the night of July 31, 1987, subionospheric VLF signals from all the transmitters listed in Table 2 were being monitored at Wallops Island, Lake Mistissini, and Stanford University. After the onset of the second particle injection event on July 31, an hour-long sequence of 24 VLF perturbation events was observed on the NAA-WI signal (Figure 5). No other such sequence was observed on this or any other signal on July 31, despite the high whistler rate, although a few isolated events were observed on the NAU signal received at Wallops Island, Lake Mistissini, and Stanford, and on the 48.5-kHz signal received at Stanford. We note that the only other extended sequence (i.e., multiple events occurring for longer than 10 min) of VLF perturbation events in continuous nightly observations during the WIPP campaign period (July 10 through August 1, 1987) occurred on the 48.5-kHz signal received at Wallops Island between 0200 and 0400 UT on July 30.

For the purposes of this study a VLF perturbation event was defined as an amplitude perturbation of at least 0.1 dB with a recovery lasting >10 s. All of the 24 perturbations on the NAA-WI signal that were identified through the strict application of these criteria were positive changes, ranging in magnitude from 0.1 dB to 0.6 dB. The first NAA-WI VLF event occurred at 0331:53 UT, about 14 min after the onset of the substorm particle injection event. Before 0350 UT the onset durations of the perturbations were about 1 s (Figure 6*a*), similar to those of VLF perturbations caused by whistler-induced electron precipitation [*Carpenter et al.*, 1984]. However, the events occurring after 0350 UT tended to have shorter (<0.5 s) onset durations (Figures 7*a*, 8*a*, and 9*a*). Some of these later VLF events were also characterized by a sharp, short duration (<0.2 s) peak seen in the amplitude of the NAA-WI signal at the termination of the event onset (Figures 7*a* and 8*a*). (Such peaks were not considered in estimating the magnitude of a VLF event.)

The onsets of all of the VLF perturbation events observed on the NAA-WI signal occurred at the times of intense ELF-VLF broadband clusters of radio atmospherics detected on the ground at Wallops Island (Figures 6*b*, 7*b*, 8*b*, and 9*c*). During the WIPP rocket flight (0355:23-0404:00 UT), similar "sferic clusters" accompanied 23 "anomalous" optical events (AOEs) observed by a down-looking optical lightning sensor on the rocket between 150 and 412 km altitude [*Li et al.*, 1991]. These included the clusters at the onsets of the two NAA-WI events observed during the rocket flight, at 0355:46 (Figure 9) and at 0356:49 UT [*Li et al.*, 1991, Figure 5]. Each AOE consisted of a number of continuous emissions separated from each other by less than 200 ms, each lasting from several tens to several hundreds of milliseconds [*Li*

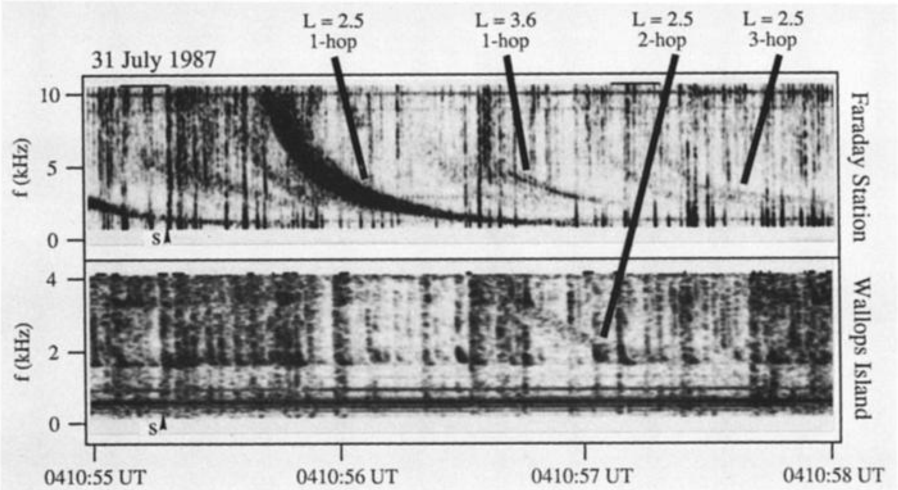

Fig. 4. Dynamic spectra of a single-source multiple-whistler event observed at Faraday Station and Wallops Island, showing one-, two-, and three-hop $L \simeq 2.5$ whistlers and a one-hop whistler at $L \simeq 3.6$. The causative sferic ("S") has been identified using a well-established technique [*Helliwell*, 1965, pp. 122-123]. A negative CG flash located by the SUNYA network at 0410:55.269 UT over the Atlantic Ocean east of Georgia (31.2°N, 75.7°W, $L = 1.9$) was probably the source of the causative sferic. The calculated subionospheric travel time from the CG flash to Faraday, assuming the group velocity to be that of light in vacuum, is about 35 ms, consistent with the delay between the sferic observed at Wallops Island and at Faraday.

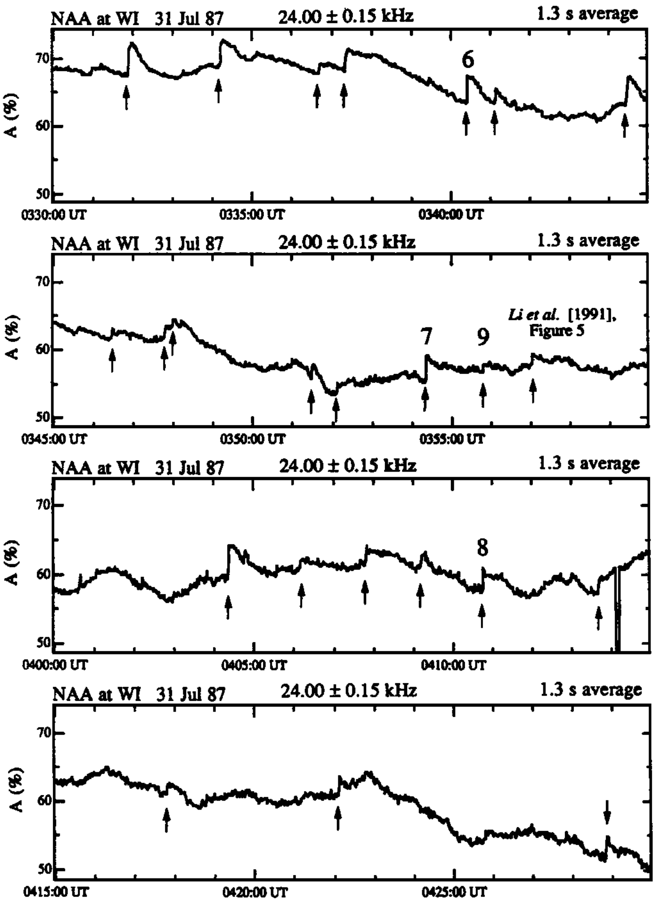

Fig. 5. Amplitude of the 24.0-kHz NAA signal observed at Wallops Island, displayed for the period on July 31, 1987 during which VLF perturbation events appeared on this signal. The signal amplitude (A), averaged over 1.3 s, is shown in percent of full scale (linear), with $A = 0$ corresponding to absence of signal. The onsets of the VLF perturbation events are indicated by arrows. Four of these are identified by the number of the figure in which they appear at higher time resolution; another is identified by the figure in which it appears in the work of *Li et al.* [1991].

et al., 1991]. Variations in the power of each AOE correlated well with temporal variations in the power of the simultaneous "sferic clusters" [*Li et al.*, 1991]. At the time of the NAA-WI event at 0355:46 UT (Figure 9*a*), the down-looking optical lightning sensors on the balloon as well as on the rocket detected nine optical impulses, two of which coincided with CG flashes detected by the SUNYA network (Figure 9*f*).

A quantitative determination of "sferic clusters" was made by analyzing the amplitude of radio noise in the 5.5±0.5 kHz range at Wallops Island, time-averaged over 0.3 s; these criteria reflect the characteristics of the "clusters." Peaks in the noise amplitude greater than or equal to the signatures of "sferic clusters" associated with VLF event onsets occurred at a rate of about 3 per minute. These peaks included about two thirds of the "clusters" that were correlated with AOEs. The "sferic cluster" occurrence rate thus determined was about the same as the AOE rate (23 in about 8 min) and was much greater than the NAA-WI VLF event rate (24 in about 1 hour).

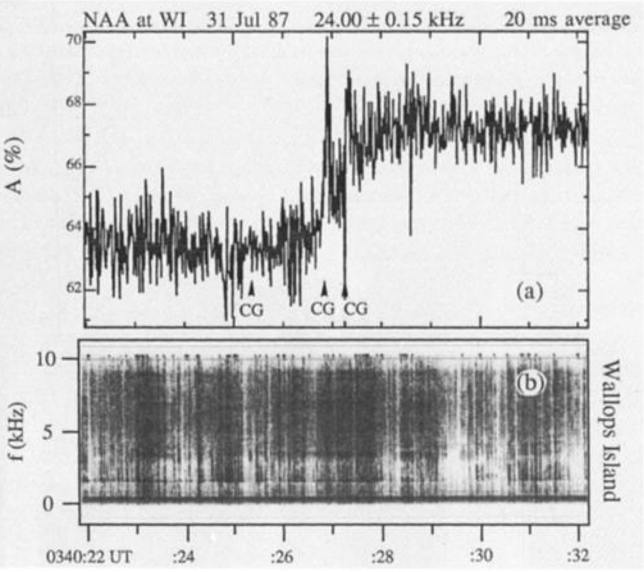

Fig. 6. (*a*) VLF perturbation event on NAA-WI (onset at 0340:26.5 UT), with (*b*) a 0- to 10-kHz dynamic spectrum of broadband data from Wallops Island. The NAA signal amplitude (A), averaged over 20 ms, is shown in percent of full scale (linear), with $A = 0$ corresponding to absence of signal. An example of a "sferic cluster" occurred roughly between 0340:26 and 0340:28 UT. Three CG flashes (indicated by arrows in Figure 6*a*) were located by the SUNYA network during the period shown here, one negative flash at 0340:25.437 near the NAA transmitter and two positive flashes at 0340:26.875 and 0340:27.283 over Long Island. Positive CG flashes were detected by the SUNYA network during the onset of only one other VLF perturbation event between 0330 and 0430 UT.

4. ANALYSIS AND DISCUSSION

In this section we examine the associations among lightning, whistlers, and VLF perturbation events and discuss possible cause and effect relationships that may have existed during the period 0330-0430 UT on July 31, 1987, including the apparent influence of the substorm particle injections on the NAA-WI perturbation events.

Sources of Whistlers Received at Faraday

By comparing the 12 min of broadband data from Faraday during the hour 0330-0430 UT (1 of every 5 min) to the corresponding minutes of SUNYA data it was determined that at least 66% of the 312 CG flashes detected by the network during these minutes produced whistlers recorded at Faraday. About 80% of all flashes and a similar proportion of whistler-causing flashes occurred within a few hundred kilometers of the NAA-WI great circle path. We note, however, that the rate of whistlers received at Faraday was more than twice the rate of CG flashes recorded by the SUNYA network (about 26 per minute). The SUNYA network measures and locates only cloud-to-ground (CG) lightning flashes; its maximum detection efficiency is estimated to be 70-80% at any point within 400 km of two direction finders [*Orville et al.*, 1983]. During the WIPP campaign this region included most of the United States east of the Mississippi River and an approximately 400-km-wide band of ocean along the coast. The whistlers not associated with CG lightning may have been excited by CG flashes that were not detected by the network, perhaps located over the Atlantic Ocean outside the region of maximum detection. Also, intracloud or cloud-to-cloud flashes, which are not recorded by the network, may have caused some of the whistlers [*Carpenter and Orville*, 1989].

Whistlers as Possible Causes of the NAA-WI VLF Perturbation Events

A causative connection between lightning in the Long Island-New England thunderstorms and the D region ionization enhancements that caused the VLF amplitude perturbations on the NAA-

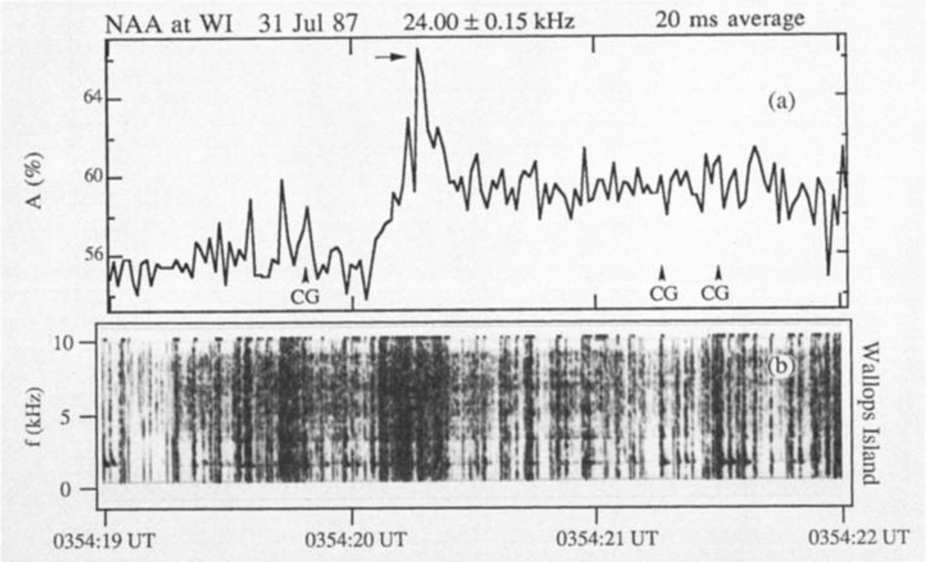

Fig. 7. (*a*) VLF perturbation event on NAA-WI (onset at 0354:20.0 UT), with (*b*) a 0- to 10-kHz dynamic spectrum of broadband data from Wallops Island. The NAA signal amplitude (A), averaged over 20 ms, is shown in percent of full scale (linear), with $A = 0$ corresponding to absence of signal. This event had a sharp, short-duration (<0.2 s) peak, indicated by an arrow in Figure 7*a*, at the termination of the event onset. A "sferic cluster" occurred roughly between 0354:19.7 and 0354:19.8 UT, and another between 0354:20.1 and 0354:20.6 UT. Three CG flashes (all negative, indicated by arrows in Figure 7*a*) were located by the SUNYA network during the period shown here, at 0354:19.812 near the NAA transmitter, at 0354:21.275 over south-central Maine, and at 0354:21.504 over South Carolina.

WI signal is suggested by the proximity of the NAA-WI great circle path to the thunderstorms and by the general lack of perturbations on other signals. Such a connection can sometimes be established by examining the temporal relationships between lightning (sferics or SUNYA network CG flashes) and VLF event onsets [*Inan et al.*, 1988*a*, *b*]. This method has been successful in cases in which strong sferics preceded VLF event onsets in a consistent fashion. In the July 31, 1987 case, however, the large number of sferics in the broadband and narrowband VLF data prevented the identification of a causative sferic for any VLF perturbation. Therefore based on the northern hemisphere VLF data alone, it could not be definitively determined whether the events were "early" or due to lightning-induced electron precipitation. The CG flash rate was also rather high (about 26 per minute), and a consistent delay between individual flashes and VLF event onsets was not apparent, again precluding definitive identification of causative lightning.

Consequently, in order to evaluate the possibility of a causal relationship between the Faraday Station whistlers and the NAA-WI VLF perturbations it was necessary to estimate the delay between a lightning flash and the ensuing electron precipitation for different electron energies. Following the model of *Chang and Inan* [1983], this delay was estimated for the July 31 conditions to be 0.35-0.50 s for direct precipitation in the north (which follows an equatorial gyroresonant interaction between a southward going whistler and counterstreaming electrons) and 0.78-0.93 s for indirect precipitation (in which the particles mirror in the north following the equatorial interaction, backscatter from the atmosphere in the south, then precipitate in the north). Comparison with data was only possible for the three NAA-WI events that occurred while broadband recordings were made at Faraday. The most plausible onset delays (measured with respect to the causative sferics of accompanying whistlers) were 1.0 s (for the event at 0340:26 UT), 0.3 s (for the event at 0355:46 UT), and 0.8 s (for the event at 0410:47 UT). (The most plausible causative whistler for the second case is labeled "1" in Figure 9*b*.) Although these measured delays are close to the calculated travel times, the probability is rather high that such a temporal association between whistlers and VLF perturbations in this case may have been merely coincidental, due to the relatively high whistler rate.

Assuming the statistics of the occurrence of whistler-producing sferics may be represented as a Poisson process with occurrence rate λ, the probability that a whistler-producing sferic occurs in a given time interval Δt is $1 - e^{-\lambda \Delta t}$ [*Inan and Carpenter*, 1986]. For the July 31, 1987, case, taking the rate of arrival of whistlers at Faraday to be $\lambda \simeq 1\ \mathrm{s}^{-1}$ and the interval preceding the onset of the NAA-WI VLF perturbations to be $\Delta t \simeq 1$ s, the probability that one VLF perturbation followed a whistler-producing sferic within 1 s is 0.63. The probability that there were three such occurrences is about $(0.63)^3 \simeq 0.25$. Based on these statistical considerations, we conclude that the data are insufficient to establish a consistent association between the whistlers and VLF event onsets that is not mere coincidence. In this connection we note that in past work, associations of whistler events and VLF perturbations were made with considerably more certainty [*Inan and Carpenter*, 1986].

Narrowband photometers on the July 31, 1987, sounding rocket failed to detect optical signatures characteristic of whistler-induced burst electron precipitation [*Massey et al.*, 1990]. However, since most of the NAA-WI great circle path lay north of the photometers' field of view, the lack of optical signatures of whistler-induced precipitation does not rule out such a cause for the two NAA-WI VLF perturbation events that occurred during the rocket flight.

In the absence of clear evidence for electron precipitation caused by ducted whistlers, other perturbation mechanisms should be considered. For example, the ionosphere above the thunderstorms, which were lined up along the NAA-WI great circle path between $L = 2.7$ and $L = 3.6$, outside the L shell range of the ducted whistlers, may have been disturbed by precipitation induced by nonducted whistlers from the same storms. Whistlers that were most probably nonducted were observed a few hours later (0800-0820 UT) on the DE 1 satellite between $L = 3.6$ and

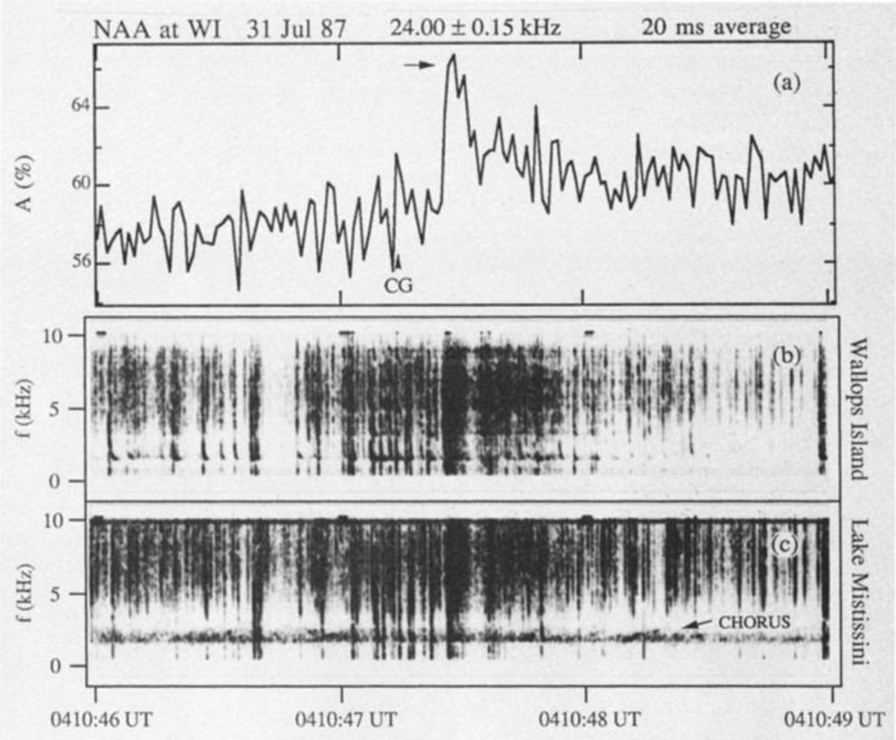

Fig. 8. (*a*) VLF perturbation event on NAA-WI (onset at 0410:47.4 UT), with 0- to 10-kHz dynamic spectra of broadband data from (*b*) Wallops Island and (*c*) Lake Mistissini. The NAA signal amplitude (A), averaged over 20 ms, is shown in percent of full scale (linear), with $A = 0$ corresponding to absence of signal. This event had a sharp, short-duration (<0.2 s) peak, indicated by an arrow in Figure 8*a*, at the termination of the event onset. A "sferic cluster" occurred roughly between 0410:47.4 and 0410:47.9 UT. One CG flash (negative, indicated by an arrow in Figure 8*a*) was located by the SUNYA network during the period shown here, at 0410:47.235 over Long Island. Chorus was evident at Lake Mistissini (indicated by an arrow in Figure 8*c*) above 1.7 kHz, the lower cutoff of the first transverse magnetic mode (TM_1) in the Earth-ionosphere waveguide [*Budden*, 1961, p. 29]. Most of the sferics at Lake Mistissini cut off below about 3.4 kHz, the lower cutoff of the TM_2 mode. The same effect is less pronounced at Wallops Island.

$L = 1.9$ at 9300 to 5100 km altitude, 80° to 105°W longitude. Nonducted whistler-induced precipitation has been suggested in a previous case where possible ionospheric disturbances were inferred to be located directly above an isolated thunderstorm center about 400 km east of Wallops Island [*Inan et al.*, 1988*a*].

Direct Coupling as a Possible Cause of the NAA-WI VLF Perturbation Events

Sferics are common sources of interference in radio receivers, including the narrowband VLF receivers used in the WIPP campaign, due to their power and wide frequency content. In particular, the sferic clusters observed on July 31, 1987, contained many strong sferics whose energy would be expected to intrude into the various channels. However, on July 31, 1987, some sharp peaks (<0.2 s duration) of unusual strength were observed only in the 24.0-kHz (NAA-WI) band at the termination of some VLF perturbation event onsets (Figures 7*a* and 8*a*) and were not visible in the amplitudes of other VLF signals. This suggests that such peaks may not simply be the intrusion into the narrowband channel of energy from strong sferics in the "sferic clusters," but also may be signatures of perturbations to the VLF mode structure in the Earth-ionosphere waveguide along the NAA-WI great circle path. A possible cause of such perturbations is localized heating of the lower ionospheric plasma by VLF radiation from lightning or other discharges, as suggested by *Inan* [1990]. The enhanced electron temperature (and thus the collision frequency) at D region altitudes within <100 km of the lightning discharges alters the local reflection characteristics of the ionosphere, leading to changes in the amplitude of subionospheric VLF signals [*Inan*, 1990]. After the heating ceases, such perturbations disappear with a cooling time constant of <1 ms [*Inan et al.*, 1991].

In contrast, the ionization enhancements at D region altitudes that cause "Trimpi" events as well as "early" and/or "fast" VLF perturbation events have recombination times of the order of 10-100 s [*Carpenter et al.*, 1984]. It has been estimated recently that >20-V/m (normalized to 100 km distance) radiation fields from lightning may accelerate (heat) electrons to energies great enough to ionize neutrals in collisions, thus creating ionization enhancements at D region altitudes that may cause "early" and/or "fast" VLF perturbations [*Inan et al.*, 1991]. Possible evidence for such a direct coupling mechanism in our data are the facts that of all the VLF great circle paths observed on July 31, 1987, only the one that lay above the active thunderstorm centers (NAA-WI, Figure 1) was significantly perturbed and that all of the event onsets were simultaneous with intense "sferic clusters." Some CG lightning flashes of sufficient strength to radiate such fields were detected by the SUNYA network in these storms; although flashes detected at the time of VLF event onsets were not among these, sufficient energy may have been radiated by the clusters to cause the additional ionization. If this were the case, then the 24 NAA-WI perturbations would be considered "early" events. In summary, if a lightning stroke radiates enough energy to create ionization enhancements at D region altitudes in addition to heating, it may cause a VLF perturbation similar to those in Figures 7*a*

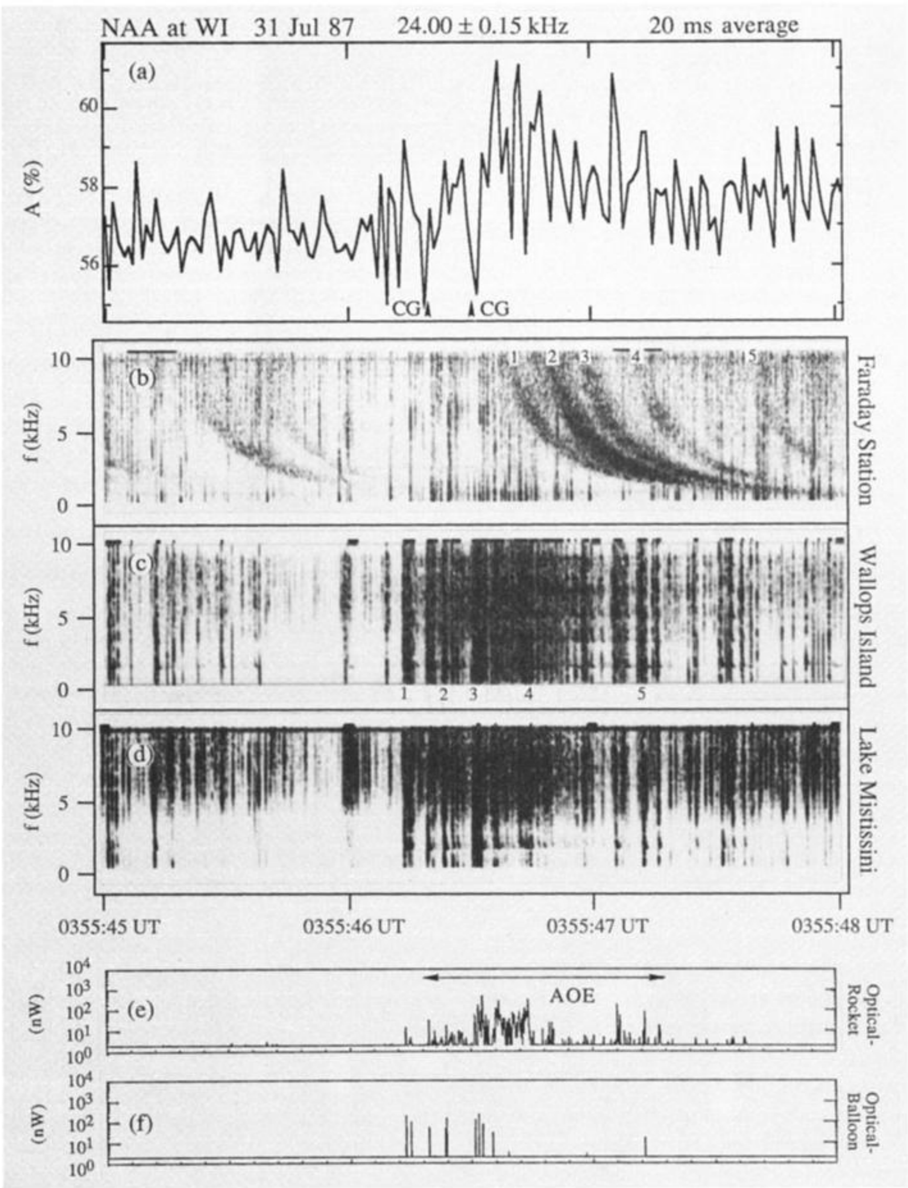

Fig. 9. (*a*) VLF perturbation event on NAA-WI (onset at 0355:46.5 UT), with 0- to 10-kHz dynamic spectra of broadband data from (*b*) Faraday, (*c*) Wallops Island, and (*d*) Lake Mistissini. We note that this is the only VLF perturbation event for which we have all possible data. The NAA signal amplitude (A), averaged over 20 ms, is shown in percent of full scale (linear), with $A = 0$ corresponding to absence of signal. Optical power data from (e) the WIPP rocket and (f) the balloon are plotted on a logarithmic scale. An "anomalous" optical event (AOE), correlated with a "sferic cluster," occurred between 0355:46.3 and 0355:47.3 UT. Two CG flashes (both negative, indicated by arrows in Figure 9*a*) were located by the SUNYA network during the period shown here, at 0355:46.327 and 0355:46.517, both over Long Island. Five sferic-whistler pairs (identified using a well-established technique [*Helliwell*, 1965, pp. 122-123]) are indicated by numbers in Figures 9*b* and 9*c*. The other VLF event that occurred during the rocket flight, along with simultaneous broadband and optical data, are plotted by *Li et al.* [1991, Figure 5*a*].

and 8*a*, with an initial, short-duration perturbation due to heating and a longer perturbation due to ionization.

Heating of ionospheric electrons by radio frequency radiation from lightning may possibly cause optical emissions localized in altitude such as AOEs [*Li et al.*, 1991] through the fine-structure excitation of N_2 in inelastic collisions by the accelerated electrons [*Inan et al.*, 1991]. In this connection it is interesting to recall that the onsets of the two VLF events that occurred during the rocket flight coincided with both AOEs and "sferic clusters" (Figure 9) [*Li et al.*, 1991, Figure 5], consistent with the suggestion that radiation intense enough to create ionization enhancements at D region altitudes could also cause optical emissions.

Possible Influence of Substorm Injections on Occurrence of VLF Perturbation Events

The only two extended sequences (i.e., multiple events occurring for longer than 10 min) of VLF perturbations observed during the WIPP campaign (July 10 through August 1, 1987) occurred after the sudden commencement on July 28, 1987, the second of these (discussed in this paper) following the onsets of the substorm injection events at 0250 and 0318 UT on July 31. Energetic electron and proton fluxes observed in the bounce loss cone by detectors on the July 31 WIPP rocket were attributed by *Arnoldy and Kintner* [1989] to these injection events. Given that the GOES 7 satellite, on which the injection events were detected, lay only slightly east of the Wallops Island meridian, the subsequent eastward gradient drift and curvature drift of the injected energetic electrons would have brought them over the greater part of the NAA-WI great circle signal path within 10 min. The interval between the onset of the second injection event (around 0318 UT) and the first perturbation event on NAA-WI (at 0331:53 UT) is consistent with this drift time. Although the particle injection events seemed to affect whistler propagation at $L \simeq 3.6$ somewhat, propagation at $L \simeq 2.5$ remained essentially undisturbed.

Based on these very limited observations, we suggest that the injection events could have enhanced the effectiveness either of whistler-induced electron precipitation or of direct upward coupling of lightning energy in causing subionospheric VLF perturbations. On the one hand, the effect of the injection events may have been to enhance the near-loss-cone distribution of trapped energetic particles, leading to the precipitation of substantially higher fluxes of electrons [*Inan et al.*, 1989]. Previous studies have reported a tendency for whistler-induced VLF perturbations near Palmer Station ($L \simeq 2.4$) to occur in the period following geomagnetic disturbances [*Carpenter and LaBelle*, 1982; *Leyser et al.*, 1984; *Inan et al.*, 1985; *Carpenter and Inan*, 1987], though the dependence is not strong. On the other hand, the particle injection events may also have established the necessary conditions for "early" VLF events or other manifestations of direct upward coupling, possibly by initiating and sustaining a steady background of drizzle electron precipitation that would increase the electron density in the D region. If this were the case, then heating and ionization due to lightning [*Inan et al.*, 1991] would tend to occur at lower altitudes, increasing the effect on subionospheric VLF signals.

5. SUMMARY

On July 31, 1987, the 24.0-kHz NAA-WI signal was perturbed repeatedly for 1 hour in a manner characteristic of VLF signatures of transient enhancements of D region ionization. Several thunderstorm centers were lined up along the 1000-km NAA-WI great circle path throughout this night, and we have shown that CG lightning flashes in these storms were the sources of whistlers observed during this period at Faraday Station, Antarctica. Although the whistler ducts were located such that whistler-induced electron precipitation could have perturbed the NAA-WI path, it could not be definitively determined from the data whether this indeed was the cause of any or all of the VLF perturbations. At least some of the ionization enhancements could have been caused by the heating of the ionosphere above the NAA-WI path by lightning [*Inan et al.*, 1991]; again, however, the analysis was inconclusive, though it is possible that phenomena such as sharp peaks at the onset of some of the events and anomalous optical events (AOEs) observed on a rocket during this period were evidence of such heating by lightning radiation. The only significant VLF perturbation activity during the period July 10 through August 1, 1987, occurred after the sudden commencement on July 28, and the NAA-WI perturbations were preceded by the onsets of two substorm particle injection events, which may have enhanced both whistler-induced particle precipitation and direct coupling of lightning to the lower ionosphere.

Acknowledgments. We have benefited from many stimulating discussions with our STAR Laboratory colleagues, in particular W. C. Armstrong. Many thanks are due C. Yang for her initial work on this data set, D. L. Carpenter for assistance in whistler analysis, and J. Yarbrough for processing the broadband data. Field support at Wallops Island was provided by W. Trabucco and T. Wolf of Stanford and W. Burns and D. Bruton, Jr., of NASA-WFF. A. C. Fraser-Smith provided the broadband data from the Stanford ELF/VLF Radiometer at Grafton, New Hampshire. The Stanford participation in the WIPP Campaign was supported by NSF-ATM-86-14987, and the subsequent research work leading to this paper was supported in part under NSF-ATM-88-04273. J. V. Rodriguez was supported during this work by a NSF Research Experience for Undergraduates grant and, later, by a NSF Graduate Fellowship. This research was supported at the University of Washington by NASA grant NAG5-604. The SUNYA lightning research program is supported in part by NSF-ATM-8703398 and by EPRI-2431-1. The University of Maryland participation in the WIPP campaign was supported by NSF grant ATM-86-15308. Additionally, the riometer and magnetometer measurements at Lake Mistissini were obtained with the support of NSF grant DPP-86-10061.

The Editor thanks R. C. Franz and another referee for their assistance in evaluating this paper.

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(Received March 8, 1991;
revised September 20, 1991;
accepted October 1, 1991.)