JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 94, NO. A7, PAGES 8886–8894, JULY 1, 1989

# The Excitation of Active Whistler Mode Signal Paths in the Magnetosphere by Lightning: Two Case Studies

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In two ~ 1 hr case study periods, the properties of whistlers propagating along multiple geomagnetic-field aligned paths from points of origin in the northern hemisphere were compared to data on the location and intensity of lightning. The whistlers were recorded at the approximately conjugate stations Lake Mistissini, Canada and Siple Station, Antarctica, while the lightning data were acquired by the SUNY-Albany lightning detection network operating in the eastern United States. In the two studies, which represented times near 0700-0800 LT and relatively quiet magnetospheric conditions, between one quarter and one half of the two-hop whistlers observed at Lake Mistissini were found to have originated in ground flashes detected by the network. The uncorrelated whistlers are believed to have originated in lightning outside the network viewing area or in undetected ground flashes within the network. However, intracloud flashes within the network area cannot be ruled out as causes of some of the uncorrelated events. We confirm evidence from other workers that lightning can excite ducted whistler paths whose ionospheric endpoints are at ranges up to 2500 km or more from the lightning location. Once in the magnetosphere, the ducted waves were found to "spread" in $L$ value by an interpath coupling process that was operative over the entire $L$ range of detected whistler paths (~1000 km in the north-south direction at ionospheric heights in one case and ~1500 km in the other). In both cases there was a single most active whistler path at $L \simeq 4.7$, at the high-$L$ limit of propagation paths within the plasmasphere. In one of the cases, lightning at $L \simeq 1.6$-$1.8$ illuminated this path through interpath coupling, after first exciting a path at $L \simeq 2.2$. In the other case, each of 15 flashes in a storm center at $L \simeq 3.5$ excited the path directly at a range of roughly 600 km. An approximately linear relation was found between the normalized first stroke peak magnetic field (which is proportional to the peak current) and whistler amplitude observed during a 10-min period. The detection of whistler waves on a particular magnetospheric path and the relative intensity of the waves in successive whistlers appear to be strongly dependent upon the field strength of the impulsive radio signal from lightning at the point of ionospheric wave injection. Meanwhile, the distribution in space of the multiple paths, the absolute wave levels on the various paths, the duration of propagation in terms of higher order echoes, and the interactions of whistlers and VLF emissions propagating on the same path are found to depend primarily upon magnetospheric propagation conditions. For example, on both days the path transmitting the most whistler wave energy to a ground receiver was the one with entrance point the most distant from the lightning source.

## 1. INTRODUCTION

Although magnetospheric whistlers have been found to originate in lightning [e.g., *Storey*, 1953; *Helliwell et al.*, 1958; *Norinder and Knudsen*, 1959], most whistler research in the last 30 years has been conducted in the absence of detailed information about the location, intensity and other parameters of the associated lightning sources. In the case of ground recordings and most recordings in space, this has been possible because of the nature of magnetospheric whistler-mode propagation; the propagation delays of a few milliseconds on the path segments lying beneath the effective lower boundary of the ionosphere/magnetosphere are small in comparison to the travel times of seconds that develop along the highly dispersive magnetospheric portions of the paths. However, without simultaneous lightning data, it has not been possible to investigate on a case study basis the specific roles played by lightning in illuminating the lower ionospheric boundary and by the magnetosphere in providing a propagation medium for the waves, nor have the conditions of coupling of lightning radiation to the magnetosphere at whistler-mode frequencies been investigated in detail. Recorded data on the parameters of cloud-to-ground lightning have recently become available for the east coast of the U.S., a region known for an abundance of middle latitude lightning activity [e.g., *Turman and Edgar*, 1982; *Orville and Henderson*, 1986] and for high rates of whistlers [e.g., *Laaspere et al.*, 1963; *Carpenter*, 1966]. It is the purpose of this paper to describe, and to interpret in terms of lightning parameters and magnetospheric propagation conditions, two case studies in which lightning data were compared to the properties of whistlers observed at ground stations in the northern and southern hemispheres.

The earliest experimental studies of relations between lightning and whistlers were conducted on a limited basis, mostly with two-hop whistlers received in the vicinity of the originating flash (i.e., signals returning along magneto-



Paper number 88JA04338.
0148-0227/89/88JA-04338$05.00

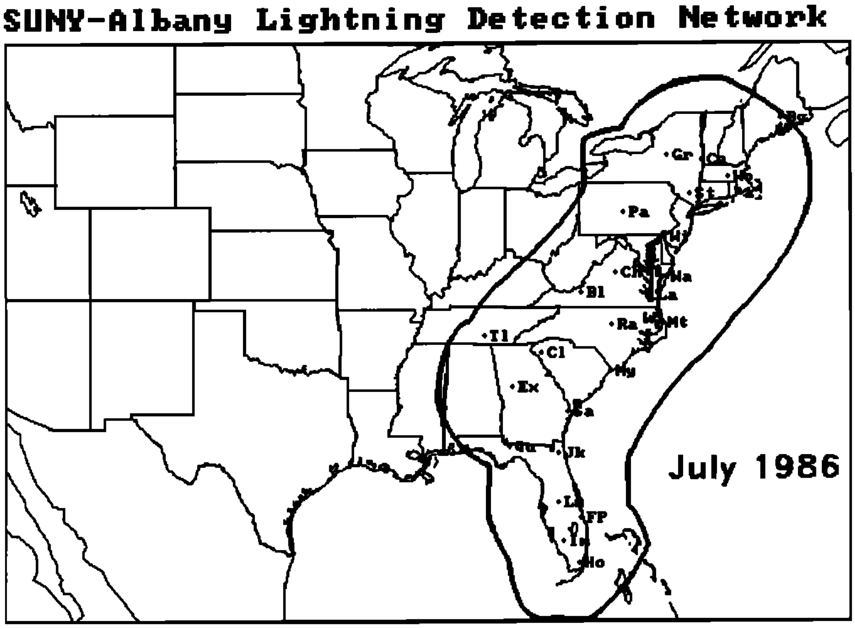


Fig. 1. Map showing the coverage of the SUNY lightning network during the July-August 1986 period of the reported case studies. The solid line shows the enclosed area where the detection efficiency for cloud to ground flashes is estimated to be 70-80%.

spheric paths after reflection in the opposite hemisphere). The results suggested that the radio atmospherics associated with whistlers tend to have peak electric fields larger than those of concurrently observed spherics not associated with whistlers [*Norinder and Knudsen*, 1959], and that the whistler-associated spherics tend to have a more pronounced peak in their amplitude spectrum near 5 kHz [*Helliwell et al.*, 1958]. In a relatively recent study by *Weidman et al.* [1983] whistlers at the magnetically conjugate stations Siple, Antarctica, and Roberval, Canada ($L \sim 4.4$), were compared to lightning measurements performed at Roberval and near the Roberval meridian at Gainesville, Florida. In a case study, it was found that whistler path entrance points in the ionosphere were being excited from locations 1500 km to over 2000 km equatorward, and a linear relation was found between two-hop whistler amplitude in the 4 to 6 kHz range and range-normalized lightning field amplitude in the same frequency interval.

In the present paper we confirm and extend the results of *Weidman et al.* [1983] on the excitation of whistler paths with ionospheric entrance points at distances of 1000-2000 km from the originating flash. In addition, we investigate the role of the magnetosphere in determining the fate of the injected waves. We use results from the approximately conjugate whistler stations Siple, Antarctica and Lake Mistissini, Canada, in conjunction with data from the recently developed SUNY-Albany lightning detection network on the east coast of the United States [*Orville et al.*, 1983, 1987]. There are two case studies, from July 7 and August 18, 1986. Both represent relatively quiet magnetospheric conditions which were themselves preceded by days of comparative calm or quiet. Both represent the near or post dawn local time sector, and both involve whistlers which propagated initially on multiple magnetospheric paths, but exhibited repeated echoing along a single most active path with ionospheric endpoints that were comparatively far from the lightning sources. In both cases there were interactions between the whistlers and VLF noise band activity on this active path. However, there were important differences between the two cases in the location of the causative lightning, and in the manner in which wave energy eventually became concentrated on the active path.

A map indicating the principal coverage of the SUNY lightning network during 1986 is shown in Figure 1. At each receiving location, information from crossed loop antennas is processed to identify cloud to ground flashes, and on the basis of coincident recordings at stations with overlapping fields of view, information is obtained on the first stroke peak magnetic field, multiplicity of strokes within the flash, and flash location [*Orville et al.*, 1983]. Theoretical estimates of peak current in the first return stroke may then be made, as discussed by *Orville et al.* [1987]. The relatively good accuracy of these estimates is supported by recent comparisons of SUNY network estimates of peak current of triggered lightning at Kennedy Space Center with direct peak current measurements of the same lightning by another group [*Henderson et al.*, 1988].

The location of the northern hemisphere whistler station Lake Mistissini (LM, 50.4°N, 74.9°W) is shown on the map of Figure 2. Siple, Antarctica, approximately conjugate to LM, is at $L \simeq 4.4$, and at 76°S, 84°W. Broadband whistler recordings (300 Hz to 30 kHz) were available on a continuous basis at LM, and on a 1-min. each 15-min. synoptic basis at Siple (the experimental VLF transmitter at Siple was operating during the intervening periods). Most of the detailed lightning/whistler comparisons were therefore made using LM records of two-hop whistlers, which had originated in the north and propagated twice along magnetospheric field-aligned paths or ducts. (Excitation of the paths is believed to occur as the result of penetration of the lower ionospheric boundary at 70-85 km altitude by radiation spreading from the originating flash in the Earth-ionosphere waveguide [e.g.,

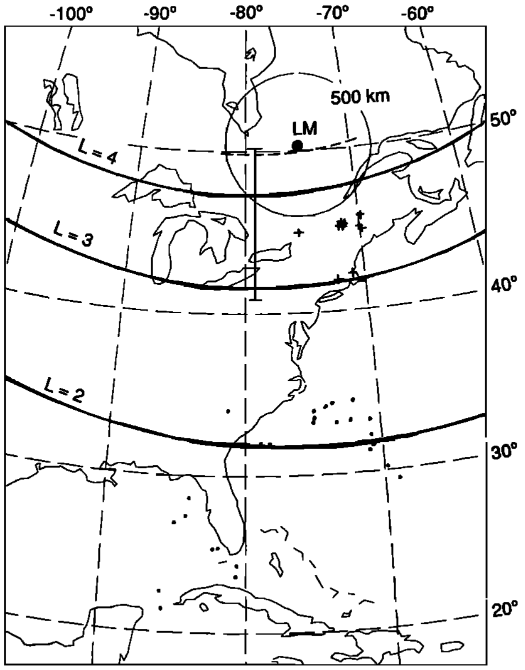


Fig. 2. Map showing the location of the whistler station Lake Mistissini (LM) and representative locations of lightning flashes detected by the lightning network during the period 1200-1230 UT on August 18, 1986. The ionospheric endpoints of multiple whistler paths excited by lightning were distributed over a north-south range indicated by the vertical bar. The most active path was estimated to have an endpoint along the dashed line segment passing near LM and within <300 km in the east-west direction.

*Helliwell*, 1965; *Walker*, 1976]. The highly refracting ionosphere causes the wave vectors of the penetrating waves to be in the near-vertical direction within the lower ionosphere, under most conditions. As the wave packets propagate upward, portions of the energy become trapped in what are believed to be field aligned irregularities or ducts, which then guide the waves to the opposite hemisphere).

Although the position of Lake Mistissini at $L \simeq 4.8$ is several hundred km poleward of the nominal northern limits of the lightning network coverage, the known high concentrations of lightning along the eastern United States coast [e.g., *Orville and Henderson*, 1986], as well as experience such as that of *Weidman et al.* [1983] (noted above), suggest that useful correlation studies can be performed in the absence of lightning stations in the immediate vicinity of LM. The broadband VLF recordings at LM contain the impulsive radio atmospherics from lightning occurring over a large part of the globe, and while these recordings are not currently processed for direction of arrival information, they permit identification of the radio atmospherics from the lightning flashes detected by the lightning network, and also provide information on the amplitude spectrum of the spherics.

## 2. EXPERIMENTAL RESULTS

### 2.1. *The Case of August 18, 1986, 1200-1230 UT*

2.1.1. *Whistlers.* Sixty-five whistlers were detected by visual inspection of spectrographic records; two examples recorded at the conjugate stations are shown in Figure 3 on spectrographic records of frequency from 1.7 to 4.2 kHz versus time. Arrows above the LM record indicate the causative atmospherics, which were straightforwardly identified for all 65 events through standard techniques, including intercomparisons of multiple events. By means of dispersion analysis [e.g., *Park*, 1972], the whistlers were found to have propagated in the plasmasphere on multiple paths with ionospheric endpoints distributed over the $L$ range ~2.9 to 4.7, as indicated by the vertical bar on the map of Figure 2. However, detailed study showed that a path with endpoints at $L \sim 4.7$ dominated the propagation, particularly after the first hop. Slanting arrows on the records of Figure 3 show the whistler component that propagated on this path and its successive echoes. Following partial reflection of the one-hop waves in the southern hemisphere, there was interpath coupling, such that portions of the reflected energy from the lower $L$ paths coupled onto the dominant path at $L \sim 4.7$. (See *Smith and Carpenter* [1982] for a recent discussion of interpath coupling.) Echoing VLF emisssion activity was observed on the active path during the hour prior to 1200 UT.

The endpoint of the $L \sim 4.7$ path is estimated to have been located along or near the dashed curve in Figure 2, and within <300 km from LM in the east-west direction. The east-west range is based upon the presence on the LM records (Figure 3, after 1205:33 UT) of strong signals from the Siple experimental VLF transmitter that were found to have propagated on the active whistler path, and upon previous analyses of the propagation paths of waves injected from Siple [*Carpenter and Miller*, 1976; *Carpenter and Bao*, 1983].

Travel-time measurements on the dominant whistler path showed an increase in group delay of several percent during the 30-min period, indicating a cross-$L$ outward drift and associated eastward electric field in the equatorial magnetosphere of about 0.15 mV/m. This is consistent with other whistler based measurements of middle-magnetospheric convection during quiet periods [*Carpenter and Seely*, 1976; *Carpenter*, 1978].

2.1.2. *Lightning.* The map of Figure 2 shows by crosses the locations of two spatially localized regions of lightning activity near 45°N and 42°N. Dots indicate a broad region of activity equatorward of 35°N. The lightning network recorded 15 ground flashes near 45°N, 14 near 42°N, and 352 in the lower latitude region. All but four of the flashes involved transfer of negative charge to ground.

2.1.3. *Relations between lightning and whistlers.* Correlations were initially determined by comparing times of lightning occurrence, rounded to the nearest previous second, with times of the causative radio atmospherics of the 65 whistlers that were read from the spectrographic records. In typical cases, time could be read on the whistler records with ~30 ms accuracy. By this method, it was concluded that all 15 of the flashes from 45°N were whistler producing, and that two of the 14 at 42°N also caused whistlers. In Figure 3, the first whistler (spheric at ~1205:12 UT) was found to be correlated, while the second (at ~1205:25 UT), although quite similar in appearance, was not. Of the whistler-producing flashes, 2 of the 15 at 45°N and 1 of the 2 at 42°N carried positive charge to ground. Later study of millisecond-resolution data from the lightning network showed that in the 17 apparently correlated cases, the mean interval between the measured radio atmospheric time at

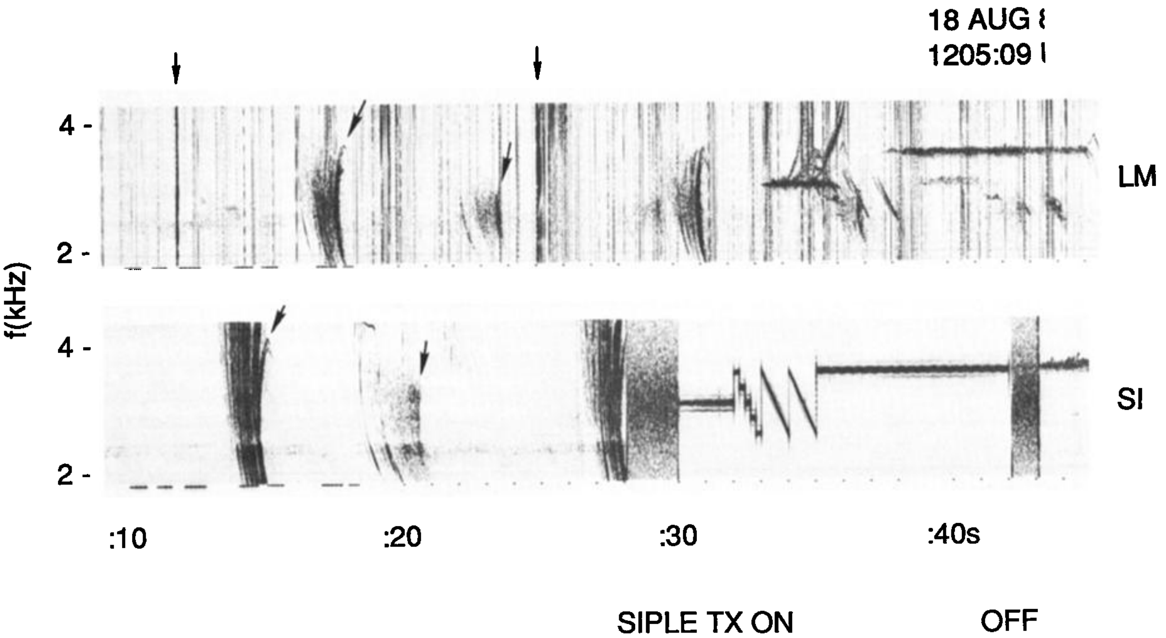


Fig. 3. Spectrograms (1.7-4.2 kHz vs time) showing whistlers recorded at the approximately conjugate stations Lake Mistissini, Canada, and Siple, Antarctica (SI), during the period of compared lightning and whistler data on August 18, 1986. Arrows above the LM record show the causative impulses of two whistlers, the first of which was found to originate in a ground flash detected by the lightning network. Both whistlers propagated back and forth between the northern and southern ends of magnetospheric paths; wave activity on the most active path is indicated for the first whistler by slanting arrows. The SI record after 1205:30 UT shows the frequency-time format of the Siple VLF transmitter. Signals from the transmitter propagated on the active path to LM; their travel time was approximately 3 s.

LM and the lightning time was 30 ms, with a standard deviation of 15 ms, which is within the uncertainty of the timing measurements. Because of the high lightning rate in the lower latitude region, there were 8 additional cases of possible correlation, based upon occurrence within the same second. However, the millisecond-resolution data showed the lightning in these cases to be randomly distributed within the second with respect to the whistler sources, and thus these events were found to be uncorrelated.

Figure 4*b* shows on a time line the occurrence at LM and the field strength, integrated over a 1-kHz band centered at 2.5 kHz, of the dominant (trailing) component of the 15 whistlers that were correlated with the flashes at 45°N. The corresponding estimated lightning peak current in kiloamperes for the first return stroke recorded by the lightning network is plotted downward. Prior to 1212 UT the correlated events occurred at a rate of about one every 80 s, and the two hop whistler amplitude was roughly propor-

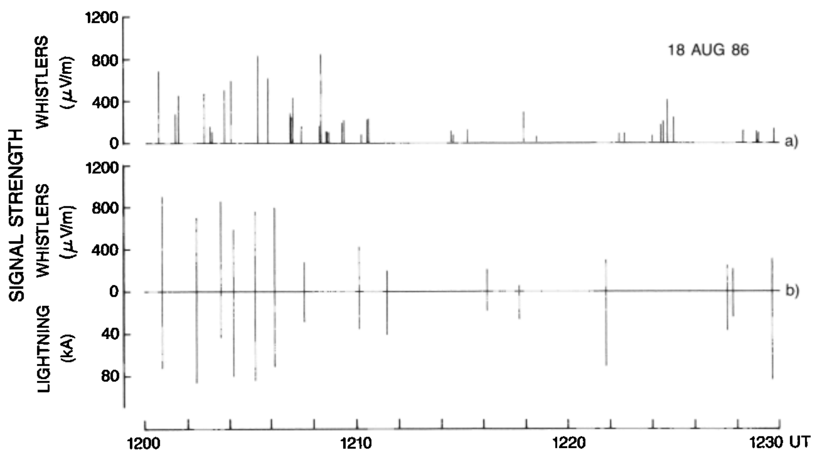


Fig. 4. Timeline display of field strength of two-hop whistlers received at LM and first return stroke peak current of lightning recorded by the SUNY lightning network during 1200-1230 UT on August 18, 1986. The whistler data represent peak amplitude at the output of a 1-kHz bandwidth filter centered at 2.5 kHz. The lightning data represent peak current. (*a*) Data for whistlers that were not identified as originating in a cloud to ground flash detected by the lightning network. (*b*) Data for the whistlers and lightning events that were found to be correlated.

tional to the lightning peak current. Following 1212 UT the event rate dropped, and the whistler amplitude did not vary widely as lightning amplitude changed.

The time line in Figure 4*a* shows amplitude information for the whistlers for which no correlated ground flash was identified. They were on average less intense than the correlated whistlers, but exhibited changes with time in field strength and rate that were roughly similar to the changes of the correlated events. There was a tendency for the lowest amplitude events to occur in pairs or clusters of three, with spacings of from 0.2 s to $\sim$ 4 s between successive events.

2.1.4. *Comments on effects of range-normalized radio atmospheric amplitude.*

In evaluating the effects of lightning peak current on whistler excitation, it is necessary to consider the effects of spreading losses on the radio atmospheric as it propagates in the Earth-ionosphere waveguide between the flash location and the entrance point of a magnetospheric path. Since LM was located relatively close to the most active magnetospheric path, the relative amplitudes of radio atmospherics recorded there were used as a coarse measure of the relative field strengths of the impulsive signals at the path entrance point. Measurements were made of wideband spheric amplitude over the important whistler frequency range of 2-3 kHz. There appeared to be a threshold spheric field strength at LM below which whistlers were not produced. This threshold was determined from the measured field strength at LM of two flashes from the 42°N region which produced barely detectable whistlers. Most of the spherics for the detected whistlers ranged from 5 to 15 dB above this threshold. Flashes occurring near or below 35°N with intensities (as measured by the lightning network) comparable to the stronger flashes in the 45°N group were recorded at LM near the threshold level, or 10-15 dB below those from the 45°N region. Considering a 1/R spreading loss, the difference in distance to LM is a factor of 3 or 4, which could explain the 10-15-dB difference, and also partially explain the lack of whistler production by the lower latitude flashes.

2.1.5. *Comments on uncorrelated whistlers.* The uncorrelated whistlers were essentially identical to the correlated events in terms of dispersion properties and the number of paths excited in the stronger events. The spectrograms and 2-3 kHz amplitude records for LM showed that radio atmospherics with high amplitude (>10 dB above the noted threshold level) occurred at an average rate of over two per minute between 1200 and 1220 UT, and at a rate of over four per minute between 1220 and 1230. These results, coupled with the facts that most of the correlated lightning events occurred at the northern periphery of the network and that a correlated flash was detected for only 27% of all whistlers, suggest that significant fraction of the uncorrelated events were produced by flashes located outside the range of the network and in the general vicinity of LM.

It is possible that some of the uncorrelated events were produced by cloud flashes or undetected ground flashes occurring in the region of the 45°N lightning activity (on average, $\sim$20% of ground flashes occurring within the network are not registered by the system). When the occurrence rate of ground flashes at 45°N dropped sharply after $\sim$1210 UT (Figure 4*b*), the occurrence rate of uncorrelated whistlers dropped in similar fashion. However, this may well have been coincidental; the magnetospheric "response" appeared to change after 1210 UT, in terms of the apparent relation of whistler amplitude to causative lightning peak current (see Figure 4*b*). Also, nearly all high amplitude radio atmospherics recorded at LM before 1210 UT were associated with whistlers, while after 1210 UT more than half were unaccompanied by detected whistler events.

A possible role of cloud flashes in producing the uncorrelated whistlers was suggested by measurements of the "duration" of whistler-associated radio atmospherics observed between 1200 and 1210 UT. In the case of each whistler, a single impulse or atmospheric could be identified on the spectrograms as being causative of the major features of the following whistler. Other impulses, typically weaker, were often present, usually following the causative spheric. However, in the cases of the correlated events, these tended to occur, if recognizable, within $\leq$ 100 ms after the causative impulse, while in at least one half of the uncorrelated events the impulses occurred over an interval of 200 ms or more. This effect is illustrated in Figure 3 by a correlated event (spheric at first vertical arrow), and by an uncorrelated event (second arrow). This greater temporal extent is consistent with evidence that electrical activity in typical cloud flashes tends to exceed in duration that of cloud-to-ground events [*Brook and Ogawa*, 1977]. However, *Malan*, [1958] has reported that the radiation fields from cloud flashes at 3 kHz were lower by a factor of 20 to 40 than the fields of ground flashes in the same storm. Such an amplitude difference was clearly not present in our study. When recorded at LM, the causative atmospherics of the uncorrelated whistlers were found to be comparable in amplitude to the spherics associated with the correlated events. Thus it appears likely that most of them originated in ground flashes that were undetected by the network.

### 2.2. *The Case of July 7, 1986, 1210-1320 UT*

2.2.1. *Whistlers.* Eighty nine whistlers were detected by visual inspection of the continuous LM spectrographic records; two examples recorded at the conjugate stations are displayed in Figure 5. Again, there was multihop echoing and propagation on multiple paths. Again, as in the case of Figure 3, only the first of the two events was correlated with a ground flash detected by the lightning network. In this case there was a strong noise band in the backround, consisting of a mixture of hiss-like noise and line like echoing emissions of the type reported by *Helliwell et al.* [1975] (the amplitude spectrum of the Siple record was distorted by parasitic effects of the newly constructed 21-km north-south horizontal antenna element). Interaction of echoing whistlers and the noise band is suggested by the growing, echoing emission near 2.3 kHz at the right of the LM record. This emission appears to have originated in echoes of the second whistler.

Detailed examination of the broadband spectra showed large departures from the approximately integral one- and two-hop relations shown in the case of Figure 3. The strongest one-hop component at Siple (slanting arrow) exhibited a much lower travel time than expected from the separations of later echoes. Following the second hop, each echo at a station appeared midway in time between echoes at the other station, as if all propagation were on the same path or cluster of closely spaced paths. The so called "third-hop

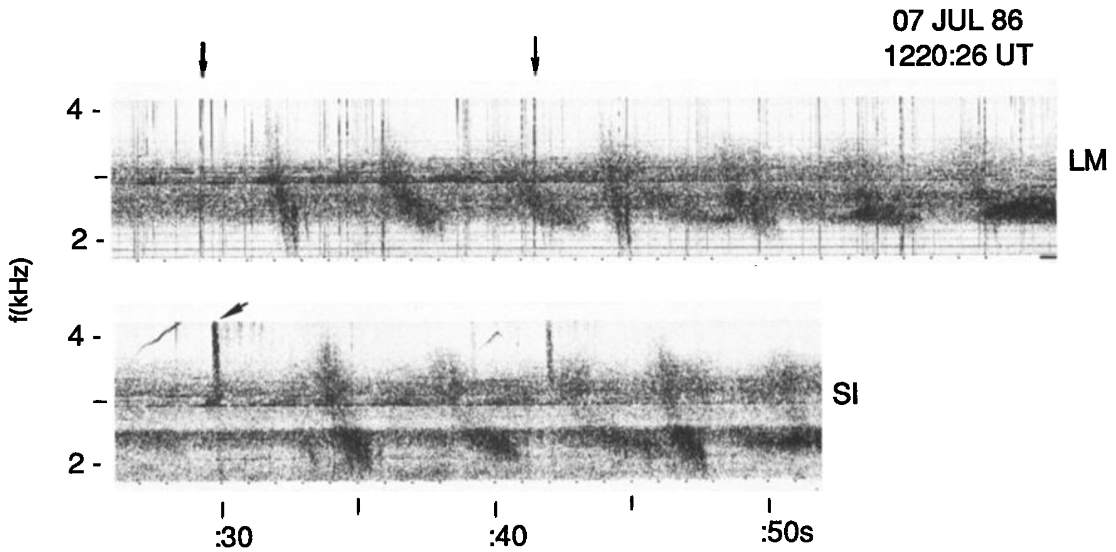


Fig. 5. Spectrograms, in a format similar to that of Figure 3, showing two whistlers recorded at LM and SI during the case study on July 7, 1986. The whistlers exhibit multihop echoing. Slanting arrows on the SI record show the strongest component of the whistler at the time of its first-hop reception at Siple. Arrows above the LM record show the causative impulses of the whistlers, the first of which was found to originate in a ground flash detected by the lightning network. The backround noise band contains a mixture of hiss-like noise and line-like features of the type reported by *Helliwell et al.* [1975]. Interaction of echoing whistlers and the noise band is suggested by the growing, echoing emission near 2.3 kHz at the right of the LM record. This emission appears to have originated in echoes of the second whistler. The amplitude spectrum of the SI record was distorted by parasitic effects of the newly constructed 21-km north-south horizontal antenna element.

anomaly" [*Carpenter and Šulić*, 1988] was present, in that the three-hop echo at Siple at 1220:35 UT was stronger near 2.5 kHz than the one-hop signal.

Figure 6 shows the one- and two-hop travel time relations in greater detail by displaying in a wider frequency band a whistler recorded later in the period. There were multiple first hop components, only the first of which is clearly seen in Figure 5. This whistler was not correlated with a detected ground flash, but was similar in detail to correlated whistlers.

Dispersion analysis of the whistlers indicated that the range of $L$ values excited during the period was $\simeq$ 2.2-4.6, as indicated by the vertical bar on the map of Figure 7 (the distribution in longitude of path endpoints is not known). Again, as in the case of August 18, 1986, there was coupling from lower latitude paths onto one or more paths at $L \simeq$

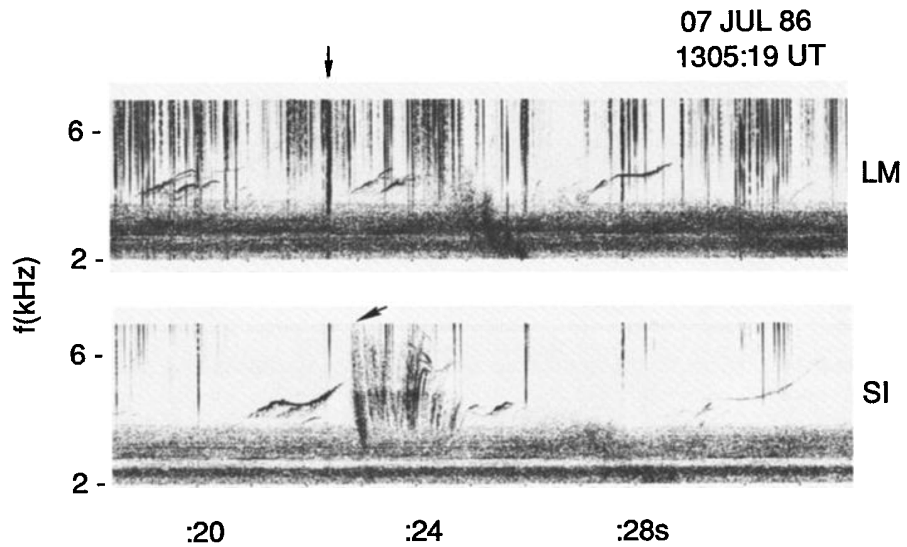


Fig. 6. Spectrograms (2-7 kHz versus time), showing in a wider frequency range some details of the first hop propagation of whistlers during the July 7, 1986, period. The event occurred less than an hour after the events of Figure 5. A slanting arrow above the SI record indicates the strong one-hop component that was also identified in Figure 5. The multiple components indicate excitation of paths distributed over the $L$ range indicated by the vertical bar in Figure 7.

4.6, near LM, apparently at the time of one-hop reflection. However, this highest latitude path or path cluster, with endpoint at latitude $A$ in Figure 7, was not strongly excited by the originating flash, and the principal contribution to subsequent wave activity on it involved coupling from the lowest latitude path, with entrancepoint at latitude $B$ in Figure 7, to the one at $L \simeq 4.6$. The process is illustrated by the simplified sketch of Figure 8, which shows by arrows the path followed by the dominant waves, and indicates the substantial difference in length between the one-hop path and the longer, active path.

2.2.2. *Lightning*. The locations of ground flashes detected by the lightning network, examples of which are shown on the map of Figure 7, were consistent with the initially strong excitation of a path near latitude $B$. There were 160 ground flashes detected (all but two involving transfer of negative charge to ground), eight near 30°N, 90°W and three at 30°N, 85°W (arrows). The remaining 149 occurred near 25°N in the region indicated by the third arrow.

2.2.3. *Relations between lightning and whistlers.* Millisecond information from the lightning network was again used to establish the correlations. Of the 89 identifiable whistlers, 35, or 39%, were correlated with ground flashes detected by the network. Five of the 8 flashes near 30°N, 90°W were correlated, as were two of the three near 30°N, 85°W, while only 28 of 149, or 19% were correlated in the region further south.

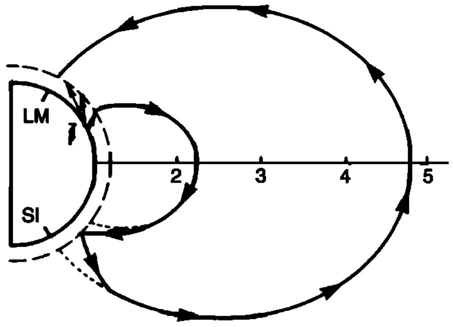


Fig. 8. Simplified sketch of the case of July 7, 1986, showing the path followed by energy that initially penetrated the ionosphere at latitude $B$ of Figure 7 and then coupled into a path at latitude $A$ at the time of ionospheric reflection in the southern hemisphere.

The amplitude distribution of the estimated first return stroke peak currents in kiloamperes in all the flashes is shown in Figure 9*a*. Shading indicates that fraction of the total in each range that were correlated with whistlers. Figure 9*b* shows the percentages of correlated flashes within signal strength bins of 0-60, 60-120, 120-180, and 180-240 kA. The stronger flash categories exhibited significantly higher percentages of correlated events. The signal strengths on this day tended to be above what is considered to be a median

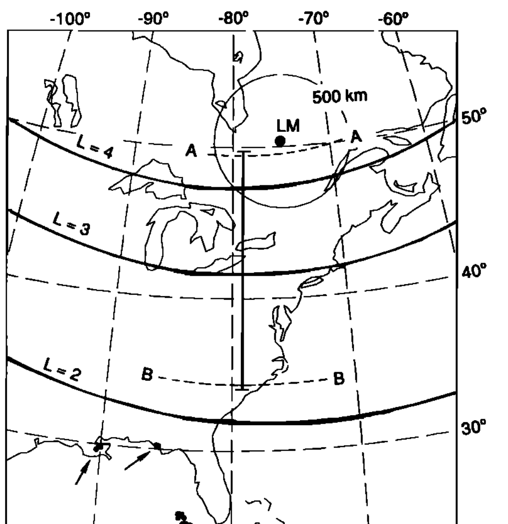


Fig. 7. Map showing the distribution of whistler path endpoints and lightning activity during the case study of July 7, 1986, 1210-1320 UT. The north-south range within which multiple whistler paths were initially excited by lightning is shown by a vertical bar. Dashed segment $A$ shows the estimated endpoint latitude of the active path along which the whistler wave energy became concentrated after the first hop of propagation. Segment $B$ show the estimated latitude of the path at $L \sim 2.2$ which was strongly excited on the first hop and which, through interpath coupling, provided the principal contribution to the later wave activity at $L \simeq 4.6$. The locations of representative lightning flashes that were correlated with whistlers are shown by arrows. All of the flashes detected in the case study period were located near Florida or along the Gulf Coast.

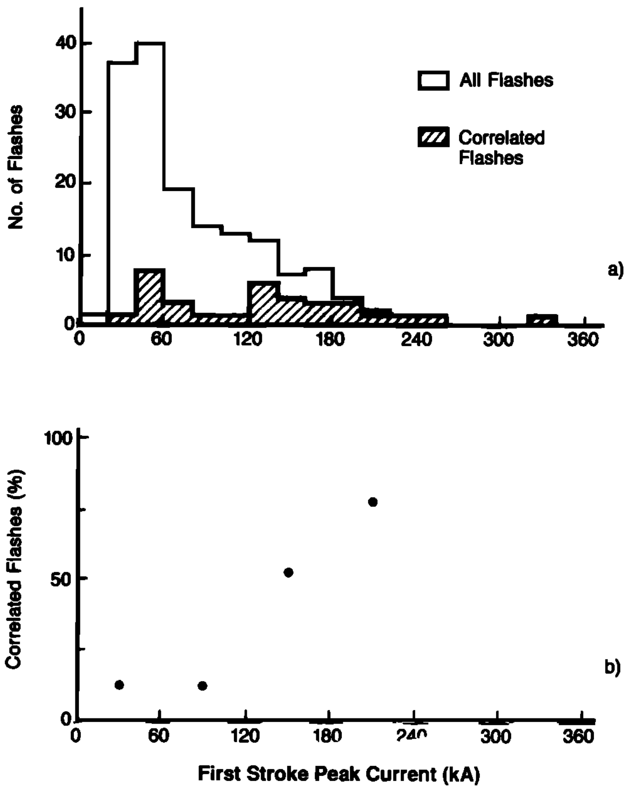


Fig. 9. *a*) Histogram showing the signal strength distribution in kiloamperes of the first return stroke peak currents in all the flashes detected by the SUNY lightning network during the 1210-1320 UT period of July 7, 1986. The number of flashes in each amplitude range that were found to be causative of detected whistlers is indicated by shading. (*b*) Percentage of flashes that were found to be causative of detected whistlers, as a function of lightning signal strength. The data were grouped in amplitude bins of 60 kA. No value is shown for the events above 240 kA.

value of about 30 kA for summer lightning events involving negative charge.

2.2.4. *Comments on effects of range-normalized radio atmospheric amplitude.* Because of the high natural noise level on the broadband records it was not possible to correlate the lightning intensity with whistler amplitude. However, the effect of range-normalized amplitude at the ionospheric entrance points of whistler paths is suggested by the large relative strength at Siple of the leading whistler one-hop component, which propagated on a path with entrance point near latitude $B$, and by the predominance of this component, which is marked by slanting arrows in Figures 5 and 6, in the later multihop propagation of the whistler.

2.2.5. *Comments on uncorrelated whistlers.* The uncorrelated whistlers again resembled the correlated ones and exhibited, in terms of visual record inspection, a comparable distribution of amplitudes. Because of the importance in all whistlers of the path near latitude B, and the lack of evidence on the LM records of atmospherics originating near the whistler receiver, we conclude that the uncorrelated whistlers originated in flashes located within the latitude range $\sim 25°$-$35°$ (Figure 7). Likely source locations are along the gulf coast to the west of the network viewing area (Figure 1), in view of the fact that efficient excitation of whistlers occurred from locations at 30°N (arrows, Figure 7) that were near the western periphery of the network. However, in order to have produced similar whistlers, the peak currents in such an extra-network flash distribution must have regularly equalled or exceeded the already above average peak currents that were measured by the network. Undetected ground flashes within the network are also a possibility, and cloud flashes within the network cannot be ruled out as sources of some of the uncorrelated events.

It is not clear why certain stronger flashes did not produce detectable whistlers. However, the whistler rate tended to vary widely, on a time scale of $\sim$10 min, independently of the detected lightning rate. During the 10 min from 1346 to 1356 UT, there were no whistlers, although six flashes with peak currents in excess of 120 kA were registered. It is also possible that the peak current of the first return stroke, as measured by the lightning network, does not provide a consistent measure of the amplitude spectrum of the lightning in the 2-4 kHz range important for the whistlers in this case.

## 3. Concluding Remarks

In two case studies near 0700-0800 LT, between one quarter and one half of two-hop whistlers observed at Lake Mistissini, Canada, were found to have originated in cloud-to-ground flashes detected by the SUNY-Albany east coast lightning network. In both cases, the uncorrelated whistlers probably originated either in lightning outside the network viewing area or in undetected ground flashes within the network, although cloud flashes within the network cannot be ruled out as sources of some of the events.

It is possible that the efficiency with which successive flashes excite detectable whistlers increases with decreasing flash rate. In one case, each of 15 flashes detected during a 30-min period within an individual storm center produced a detected whistler.

In our two case studies the availability of whistler records from both hemispheres (Lake Mistissini, Canada, and Siple, Antarctica) was found to be essential to an interpretation of the magnetospheric response to lightning. In agreement with the work of *Weidman et al.*, [1983], we found that lightning could excite ducted whistler paths whose ionospheric endpoints were as far as 2500 km or more from the lightning location. Once in the magnetosphere, the ducted waves were found to "spread" in $L$ value by the process of interpath coupling. In one case, the spreading occurred over a distance of $\simeq$ 1000 km in the north-south direction, and in the other over a distance of $\simeq$ 1500 km.

The spatial nonuniformity of the magnetospheric response to lightning is illustrated by the reported excitation of "active" magnetospheric paths, along which the integrated growth was substantially higher than on other paths that were excited. In one of the cases, lightning at $L \simeq 1.6$-$1.8$ illuminated such a path through interduct coupling, after first exciting a path at $L \simeq 2.2$. In the other case, each of 15 flashes in a storm center at $L \simeq 3.5$ excited an active path directly at a range of roughly 600 km. Within the plasmasphere, and in the aftermath of weak to moderate magnetic storm activity, active paths or clusters of paths tend to lie at the higher $L$ shells, near and beyond $L = 4$, and hence are poleward of most regions of lightning activity. In both the present work and that of *Weidman et al.* [1983], the excitation over distances of 2000 km and greater took place in the generally poleward direction from the lightning sources.

In study of a $\simeq$ 10-min period, we found, as did *Weidman et al.* [1983], a linear relation between lightning intensity and two-hop whistler amplitude over part of the whistler frequency range. The whistler component whose amplitude was measured propagated on an active path that was characterized by echoing. The measurement range was below the whistler nose frequency, and hence in a frequency range (relative to the nose frequency) within which long enduring echoing, often without spectral evidence of fast temporal wave growth or excitation of VLF emissions, is regularly observed.

Within large portions of the plasmasphere, the integrated whistler-mode gain along field-aligned ducts is usually small enough such that whistlers are not detected after the second or third hop. In such regions the intensity of received whistler components appears to depend roughly upon distance from the source to the ionospheric entrancepoints of the paths. However, in other regions, most often in the outer plasmasphere, the integrated gain may be substantially higher than elsewhere. On such paths, higher order echoes, strong VLF emission activity, and interactions between whistlers and VLF emission bands may be observed. The higher gain, in addition to the common phenomenon of interduct coupling, can lead to a concentration of whistler wave energy on paths that may be at distances of over 2500 km from a source flash.

In summary, the detection of whistler waves on a particular magnetospheric path and the relative intensity of the waves in successive whistlers have been found to be strongly dependent upon the strength of the radio atmospheric at the point of ionospheric wave injection. Meanwhile, the distribution in space of the multiple paths, the absolute wave levels on the various paths, the duration of propagation in terms of higher order echoes, and the interactions of whistlers and VLF emissions propagating on the same path are found to depend upon propagation conditions within the ionosphere/magnetosphere.

*Acknowledgments.* The research at Stanford was supported by grants DPP 83-17092 and DPP 86-13783 from the Division of Polar Programs of the National Science Foundation. The research at SUNYA was supported in part by the National Science Foundation under NSF grant ATM 87-03398.

The Editor thanks M. Uman and another referee for their assistance in evaluating this paper.

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(Received June 28, 1988;
revised October 17, 1988;
accepted November 16, 1988.)