Stroke- and Space-Resolved Slit Spectra of Lightning*

by

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Addendum to Vol. I, LA-3755*  

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* Other volumes covering different aspects of the 1965 ARPA-AEC Joint Lightning Study at Los Alamos are:

LA-3755 Volume II. The Lightning Spectrum as Measured by Collimated Detectors, Atmospheric Transmission, Spectral Intensity Radiated, July 1967

LA-3756 Volume III. Propagation of Light into All-Sky Detectors, in preparation

LA-3757 Volume IV. Discrimination and False Alarm Analysis, in preparation
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STROKE AND SPACE RESOLVED SLIT SPECTRA OF LIGHTNING

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ABSTRACT

Twenty-four stroke-resolved slit spectra of lightning taken in 1966 are presented, one of which is also the first space-resolved slit spectrum of a return stroke.

These split spectra unambiguously show that the lightning return-stroke channel is a strong continuum source and that the continuum observed in the slitless spectra in 1965 is real and not the result of line radiation scattered from natural backgrounds such as clouds, haze, or rain.

Reduced slit and slitless lightning spectra now available indicate differences among strokes, both in continuum shape and relative line intensity. For most strokes the continuum can be fitted by a straight line, and the measured 3900- to 6900-Å continuum ratio varying between 1.3 and 2.4 can be explained by an optically thin bremsstrahlung source with electron temperatures between 18,000 and 50,000 K. Some strokes have a ratio larger than 2.4, and may be intermediate between optically thick and thin, since at a given electron temperature this ratio becomes larger as the source becomes optically thicker. Other continua cannot be fitted by a straight line, and some of these agree with published results. The spectrum near 3914 Å is essentially continuum.

A blend of HII, OI, and OII multiplets near 4650 Å is much stronger for slit spectra than for slitless, but all-sky photometric data show that this feature is variable. Furthermore, the intensity of multiplets between 4000 and 4250 Å agrees with slitless spectra for some strokes, while for others it is much stronger. These variations indicate real differences in the data sample, not instrumental effects.

The average width at half-intensity is the same for slit and slitless spectra for all strong line features except Hα. One possible explanation is that the channel's electron density, which determines Stark broadening of Hα, averaged twice as large in the 1965 study as in 1966.
Another possibility, suggested by the space-resolved spectrum, is that in some of the slitless spectra the observed Hγ line width was partly due to its space profile. In agreement with slitless spectra, the Hγ line is generally weaker for first than for subsequent return strokes, and the ratio of NII to N1 radiation and the slope of the continuum indicate a higher temperature, on the average, for first return strokes.

For those strokes whose continuum is fitted well by a straight line, the 5000-Å blend of NII multiplets looks like a good lightning discriminant for Vela systems. For strokes whose continuum drops strongly from 4000 to 5400 Å and rises again at longer wavelengths, it seems less feasible. A quantitative treatment of the best channel for discrimination must be delayed.

The space-resolved spectrum shows that the time- and wavelength-integrated brightness of the line radiation from three strong line features at 4830, 5000, and 5680 Å, and of the total visible light, falls to half central brightness ~ 8 meters from the channel center, while 6563 Å line radiation falls to half central brightness in ~ 34 meters and is above instrument threshold out to ~ 120 meters. Emission at such large distances must be caused by lateral corona currents. This was an unusual stroke, and dimensions of all other strokes were too small to be resolved.

I. INTRODUCTION

During data reduction of stroke-resolved slitless lightning spectra obtained as part of the 1965 ARPA-AEC joint lightning study at Los Alamos, the question arose whether what appeared to be continuum in the slitless spectra might not be due largely to light scattered from clouds, rain, and aerosol near the channel. An attempt was made in the summer of 1966 to answer this question. The NREL lens and grating spectrograph used for the slitless spectros- copy and described earlier was operated with a vertical entrance slit at the focus of the objective lens and with a 90° image rotator in front of the objective lens. With this arrangement a vertical lightning channel is imaged horizontally across the vertical entrance slit. If there is no light scattered near the channel, and if the channel diameter is unresolved by the objective lens, that part of the channel imaged on the entrance slit acts as a pinhole entrance aperture and its spectrum is displayed as a horizontal line in the film. If, however, a significant amount of light is scattered or emitted on either side of the channel, then the spectrum of this light is displayed above and below the spectrum of the channel core.

Hundreds of stroke-resolved slit spectra of lightning were obtained in the summer of 1966 by this technique, but only 24 were judged suitable for reduction and reported here. Only one of the 24 had sufficient light scattered or emitted near the channel to give an exposure allowing spatial resolution of this light.

II. STROKE-RESOLVED SLIT SPECTROSCOPY OF LIGHTNING

A. Apparatus

The spectrograph used is the NREL lens and grating spectrograph with a film-aperture ratio of f/2.8 and a dispersion of 90 Å/mm. A 90° image rotator made of two glass prisms was placed in front of the objective lens to image the vertical lightning channel horizontally across the vertical entrance slit. The spectrograph's horizontal field of view was 16°. The spectra taken on September 7, 1967 were obtained using a 200-μ entrance slit (this corresponds to ~ 6.5 Å in the film plane); for all
other spectra the slit width was 100 μ. The width at half-intensity for lines of a mercury source was 5 ± 1 μ (the entrance slit width was 100 μ, and the densitometer slit width was 25 μ). To improve the signal-to-noise ratio in the lightening spectra, they were densitometersed with a slit 125-μ wide, giving an instrumental width of ~ 10 μ for the reduced spectra. Eastman Kodak 2443 film was used.

The spectrophotograph calibration was determined at 50-μ intervals. The calibration and method of data reduction have been described earlier.

B. Results and Discussion

1. Reduced spectra - The 2% spectra are presented in Figs. 1 through 24, at the end of this report. The obsclines in each case is wavelength in Angstroms, and the ordinate is time-integrated flux (erg/cm²) at the entrance slit. This flux emanates from a vertical length of channel specified in the figure caption. Each spectrum is corrected for air and water vapor transmission, but it was not possible to correct for rain transmission.

2. Continuum shape - The continuum level is reasonably easy to determine between 4500 and 6000 μ, but for some spectra it is difficult to say whether there are strong bumps in the continuum between 4000 and 4500 μ and between 6400 and 6700 μ, or whether these bumps are due to a high density of overlapping lines. There is no correlation between the presence or absence of these bumps and the magnitude of the flux at the entrance pupil which would indicate an instrumental effect or error in calibration.

Between 6400 and 6700 μ the strongest identified lines are Hα and NII (20, 21, 22, 31), as can be seen, for example, in Fig. 7 (count 32, scan 3). The lines are sharp, and there is no bump. However, Figure 5 (count 32, scan 1), which has about the same continuum level (4500 to 6000 μ), shows a bump in this wavelength region. If the bump is due to the same lines, they must have become exceedingly diffuse. Orville’s time-resolved spectra show that the Hα feature can be extremely broadened by the Stark effect in the first few microseconds of a return stroke, and, since the quartet-quartet NII transitions are also strongly broadened by the Stark effect, it is conceivable that in the early time history of the stroke these lines could be strongly broadened and produce the observed bump.

To appreciate the problem of determining the continuum level between 4000 and 4500 μ, consider again Figs. 5 through 7 which are spectra of three return strokes of one flash. If the level of the continuum were drawn just below the obvious lines features, then in Fig. 5 there would be a sharp rise in the continuum near 4500 μ and a sharp drop again near 4000 μ; in Fig. 7, the rise and drop of the continuum in this same wavelength range are not so sharp, and in Fig. 6 there is a question whether the continuum really rises quickly at 4500 μ and drops sharply at 4000 μ, or rises gradually from 4600 to ~ 4100 μ with a strong absorption feature near 4300 μ (there is a well-documented but unidentified atmospheric absorption feature at ~ 4300 μ which has been observed by Rusjan workers).

Strong, sharp, 200- or 300-μ wide bumps in the continuum are difficult to explain theoretically, as are absorption bands that are strong in one stroke of a flash and absent from the next stroke. It would be most satisfying to conclude that the bumps are due to lines, but there may also be theoretical problems for this conclusion, since the ratio of the total energy radiated by NII (12, 40, 50, 65, 42, 55, and 45) to that radiated by NII (1) is only ~ 2 at 20,000°K, ~ 6 at 40,000°K, and the ratio of the total energy radiated by NII (10, 4, 4, and 5) to that by NII (12) is ~ 8.3 at 10,000°K or ~ 6.6 at 40,000°K. It is therefore impossible to account for the bump quantitatively in all cases by considering only the NII and NII species.

A large fraction of the spectra can be closely fitted by a straight line if the strong bumps discussed above are attributed to line radiation. The shape of the continuum for these strokes is then in agreement with that reported in LA-3754, and can be explained by a bremsstrahlung source. For electron temperatures between 18,000 and 28,000°K, optically-thin bremsstrahlung continua have a fairly linear wavelength dependence throughout the visible, with a 3900- to 6900-μ continuum ratio of ~ 1.3 at 18,000°K, and ~ 1.6 at 28,000°K. Even at electron temperatures as high as 50,000°K, the visible continuum, although becoming slightly concave, can be fitted by a straight line to within 10%, and the 3900- to 6900-μ continuum ratio is ~ 2.4. Larger ratios result at a
given electron temperature as the source becomes optically thicker.

There are spectra (see Figs. 6, 9, 19, 21) which are not simply explained in terms of bremsstrahlung radiation. Their continuum falls so fast from 4000 to 5500 Å that it must be assumed that the early high temperature phase of the channel was intermediate between optically thin and thick, while the rise in the continuum towards longer wavelengths could be due to emission, either of long duration or at higher than normal electron densities, late in the channel history when electron temperature had dropped below 11,000K.

The continuum spectrum agreement for slit and slitless spectra is good. The best agreement is between the first return stroke (slitless spectrum) of run 40, count 171, September 7, 1966. For these two strokes, even the line-to-continuum ratio is about the same, although there is a slightly different intensity distribution among the lines. As for the 1965 spectra, the continuum generally falls off more quickly from blue to red for first return strokes than for subsequent return strokes, indicating a higher temperature for first return strokes in most cases.

The spectra have been compared with continuum spectra published by Orville and Shanahan, and certain of their continua are found to agree with spectra shown here in Figs. 5, 6, 9, 17, 19, and 21 except that in a few cases their continuum at 5000 Å is too large for agreement. Many spectra presented here have continua which is too linear throughout the visible to agree with Orville and Shanahan's results, and they have a few strokes whose continuum is too strongly peaked near 4000 Å to agree with my results, but this is probably due to differences in data sample.

### Table I

Average Half-widths of Line Features for Slitless and Slit Spectra

<table>
<thead>
<tr>
<th>Wavelength of Feature (Å)</th>
<th>3995</th>
<th>5000</th>
<th>5500</th>
<th>5890</th>
<th>6158</th>
<th>6478</th>
<th>6653</th>
<th>6964</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slitless Half-width (Å) *</td>
<td>942</td>
<td>1743</td>
<td>1542</td>
<td>1944</td>
<td>2645</td>
<td>2043</td>
<td>2743</td>
<td>2243</td>
</tr>
<tr>
<td>Slit Half-width (Å) *</td>
<td>842</td>
<td>1842</td>
<td>1644</td>
<td>1946</td>
<td>2444</td>
<td>1945</td>
<td>1842</td>
<td>2243</td>
</tr>
</tbody>
</table>

* Not corrected for instrumental width.
NII to Hβ radiation, which is a measure of the degree of excitation, is larger for first than for subsequent return strokes.

4. Space-resolved lightning spectrum — The spectrum in Fig. 22 corresponds to a densitometer trace made along the dark central part of the space-resolved spectrum. Other densitometer tracings were made at 50 µ intervals on both sides of the first, out to 200 µ. There is actually exposure out to 400 µ, but that beyond 200 µ became too poor to yield good spectra. This exposure is not due to time smear, because two photoelectric channels (at 3914 and 6563 Å) whose field of view included ~ 200 meters of the lightning channel indicate that the intensity of the channel rose and decayed two decades in about 500 to 600 µsec. The channel would have had to radiate for ~ 16 msec if the exposure were due to time smear. Furthermore, it is not due to overexposure, since other spectra of greater exposure do not show this effect. The exposure is therefore due to light emitted or scattered either side of the center of the vertical channel.

The apparent brightness 28 meters from the channel center is orders of magnitude greater than would be expected for light scattered either from heavy rainfall or from a cloud behind the channel. Furthermore, the strong change in shape of the continuum at points away from the channel center indicates that the scatterers or reflecting surfaces are dispersive. I must therefore conclude that there is strong light emission from points as far as 31 meters from the channel center, and that at 6563 Å the apparent brightness is above threshold out to ~ 190 meters.

The time- and wavelength-integrated brightness of all visible light (all line plus continuum radiation between 3900 and 6900 Å except the Hα line) emitted by the channel falls off exponentially as a function of distance from channel center out to approximately 31 meters, at which point it still decreases, but quite slowly. A similar dependence was found for atomic line emission of three strong line features at 4630, 5000, and 5680 Å, and in all four cases the brightness dropped to half the channel center brightness in ~ 8 meters. However, the time- and wavelength-integrated brightness of the Hα line has an exponential dependence out to at least 62 meters, and has dropped to half central brightness in ~ 34 meters.

The fact that the half-width of the spatial brightness profile is four times larger for Hα than for the other emission lines or for the total visible light can also explain the difference in Hα line width for the slit and slitless spectra.

The continuum for the channel core can be fitted very well by a straight line throughout the visible except for a slight bump in the vicinity of Hα. It is ~ 15 meters from channel center, however, the continuum has a strong, broad bump peaking near 4750 Å and another peaking between 6500 and 6700 Å. There are minima at ~ 5700 and 4150 Å with a rising continuum at wavelengths shorter than 4150 Å. The shape of the continuum for the channel core can be explained in terms of bremsstrahlung radiation, but I presently have no physical interpretation for the shape of the continuum at points off channel center.

I can only conclude that the emission at such great distances must be excited by a lateral flow of current between the lightning channel and highly charged air surrounding it. To demonstrate the plausibility of this, Fig. 25 shows an enlarged photograph of a lightning flash from the 15-5 study (count 395 of run 30). It was taken at night using a red filter (~ 500-Å half-width, peak at ~ 6550 Å) in front of a 65-μm, f/4 lens. The range was measured as 13.4 km by photographic triangulation. The main channel between cloud and ground is ~ 2.4 km long. There are many branches off the main channel into the surrounding air, indicating that the air was highly charged. The width of these branch strokes indicates the resolution limit of the camera. The main channel to ground consists of a bright core, whose diameter is also unresolved by the camera, and a broad emitting region whose diameter varies from ~ 150 meters near the cloud to ~ 200 meters near the ground. The uniformity of the brightness in this region leads me to conclude that the emission is due to a coronal-type discharge.

Lateral corona currents were first discussed by Bruce and Golde to explain observations of electric field changes, and have been created mathematically by Pierce and by Hao and Bhattacharya. The time history of such phenomena is about one to a few milliseconds so that little or no time smear would.
be expected if the record for count 91, and the 
symmetry of the exposure indicates that there was 
no time smear.

In the discussion of lateral corona currents 
just mentioned, the current is said to drain away 
charge deposited along the path of the stepped 
leader, and the discharge of stepped leaders has 
been reported to vary between 1 and 10 meters.42 
The emission 100 meters from the channel must there-
fore be caused by draining away of charge which 
was not deposited in the air by the stepped leader.

The fact that the H_\alpha emission becomes so much 
stronger relative to the rest of the spectrum is 
also consistent with a corona current excitation 
process, for it is well known that water drops in 
high electric fields (\text{F}_0^* \text{like that would exist be-
tween the channel core and the surrounding sur-
face charge}) give off a corona discharge.4243 This dis-
charge at the surface of the drop could produce large 
quantities of hydrogen even when the temperature be-
came too low to excite NII or bremsstrahlung contin-
um radiation.

III. CONCLUSIONS

In L-3754 it was concluded that the image of 
the lightning channel at the entrance aperture did, 
indeed, act as an entrance slit, and that the conti-
um seen by the slitless spectrograph was there-
fore truly continuum. The slit spectra unambigu-
ously show that the lightning channel is a strong con-
tinuum source and that the spectrum near 1914 \AA 
is essentially continuum. Furthermore, considering 
only those strokes from 1966 which gave good spectra, 
only one in 28 gave significant exposure at distances 
of one resolution limit beyond the channel center. 
For 23 of the 28, the channel image at the entrance 
aperture would, indeed, have acted as an entrance 
slit if this spectrograph had been operated in a 
slitless mode. There are, however, storms such as 
rain 30 of the 1965 lightning study in which a large 
fraction of the flashes photographed show strong 
emission out to large distances either side of the 
main channel, and a great deal of braying of the 
main channel also the highly charged air. For such 
storms the assumption that the channel image acts 
as an entrance slit might not be valid. However 
pictures of the 1966 flashes for which spectra were 
obtained show little channel branching and no emis-
sion about the unresolved channel core, so the as-
sumption must be considered valid.

The larger sample of reduced lightning spectra 
now available indicates differences in the spectrum 
of lightning for different strokes, both in the shape of the continuum and in the relative intensity 
the lines. The width of the H_\alpha line was, on the 
average, larger for the 1965 slitless spectra than 
for the 1966 slit spectra. This is possibly due to 
a factor of two difference in electron density in 
the volume emitting H_\alpha, or part of the width of the 
line might have been due to a spatial profile in the 
case of the slitless spectra.

Agreement has also been found between the conti-
uminum of a few strokes and a few of the results 
published by Orvillle and Ussan.6 Many of the strokes 
have a continuum that can be fitted well by a 
straight line and can therefore be explained in 
terms of a bremsstrahlung source. In some cases the 
large 5000- to 6000-A continuum ratio suggests that 
the continuum is intermediate between optically thin 
and thick.

The space-resolved lightning spectrum shows 
strong volume emission out to \approx 50 meters from the 
channel core, and in the vicinity of this emission 
is above the instrumental threshold out to \approx 120 
meters. This emission has been attributed to excita-
tion by lateral corona currents.

Since a qualitative discussion was presented in 
L-3754 regarding the possibility of using a narrow 
channel at 5000 \AA for lightning discrimination for 
Vela Sierra de-tection systems, a comment about the 
behavior of the slit spectra on this problem is ap-
propriate. The slit spectra, whose continuum can be 
fit by a straight line and for which the blend of lines 
between 4000 and 4250 \AA is weak to moderate 
strength, are very similar to the slitless spectra. 
Consequently, for these, a 20-\AA-wide discrimination 
channel centered on the blend of NII multiplet near 
5000 \AA may be as good or better a discriminant, under 
a variety of storm and background light conditions, 
than one at either 4150 or 569 \AA. For the slit 
spectra for which the blend of lines between 4000 
and 4250 \AA is strong or for which the continuum drops
steeply from 4000 Å toward longer wavelengths, a 5000-Å channel will not be so much better then, and may not be so good as, a 4150- or 6565-Å channel. However, a quantitative treatment of the best channel for discrimination must be delayed for presentation in another report. 10

ACKNOWLEDGMENTS

I thank Herman Hoerlin for pointing out the desirability of having stroke-resolved slit spectra of lightning, and G. E. Barasch for his helpful discussions and for his correlated data from collimated photometers. I thank C. Stevens for his help with calibration of the spectrograph, L. M. Duncan for her effort in densitometry and the running of computer programs, and D. L. Stem for illustrations. I also thank Mrs. Sul for her fine secretarial work.

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REFERENCES


Fig. 1. Flux at spectograph entrance pupil from ~ 6-meter length of channel, uncorrected for rain transmission. First return stroke.
Fig. 2. Flux at spectrograph entrance pupil from ~ 6-meter length of channel, uncorrected for rain transmission. Subsequent return stroke.
Fig. 3. Flux at spectrograph entrance pupil from ~6-meter length of channel, uncorrected for rain transmission. First return stroke.
Fig. 1. Flux at spectrograph entrance pupil from ~1.6-meter length of channel, uncorrected for rain transmission. First return stroke.
Fig. 5. Flux at spectrograph entrance pupil from ~31-meter length of channel, uncorrected for rain transmission. First return stroke.
Fig. 6. Flux at spectrograph entrance pupil from ~ 51-meter length of channel, uncorrected for rain transmission. Subsequent return stroke.
Fig. 7. Flux at spectrograph entrance pupil from ~31-meter length of channel, uncorrected for rain transmission. Subsequent return stroke.
Fig. 8. Flux at spectrograph entrance pupil from ~15-meter length of channel, uncorrected for rain transmission. First return stroke.
Fig. 9. Flux at spectrograph entrance pupil from ~20-meter length of channel, uncorrected for rain transmission. First return stroke.
Fig. 10. Flux at spectrograph entrance pupil from ~16-meter length of channel, uncorrected for rain transmission. First return stroke.
Fig. 11. Flux at spectrograph entrance pupil from ~16-meter length of channel, uncorrected for rain transmission. Subsequent return stroke.
Fig. 12. Flux at spectrograph entrance pupil from ~16-meter length of channel, uncorrected for rain transmission. Subsequent return stroke.
Fig. 13. Flux at spectrograph entrance pupil from ~16-meter length of channel, uncorrected for rain transmission. Subsequent return stroke.
Fig. 14. Flux at spectrograph entrance pupil from ~16-meter length of channel, uncorrected for rain transmission. Subsequent return stroke.
Fig. 15. Flux at spectrograph entrance pupil from ~16-meter length of channel, uncorrected for rain transmission. Subsequent return stroke.
Fig. 16. Flux at spectrograph entrance pupil from ~17-meter length of channel, uncorrected for rain transmission. First return stroke.
Fig. 17. Flux at spectrograph entrance pupil from ~17-meter length of channel, uncorrected for rain transmission. Subsequent return stroke.
Fig. 18, Flux at spectrograph entrance pupil from ~16-meter length of channel, uncorrected for rain transmission. First return stroke.
Count 87  Scan 1 9/7/66
Range = 7.30 km

Fig. 19. Flux at spectograph entrance pupil from ~ 23-meter length of channel, uncorrected for rain transmission. First return stroke.
Fig. 20. Flux at spectrograph entrance pupil from ~16-meter length of channel, uncorrected for rain transmission. First return stroke.
Fig. 21. Flux at spectrograph entrance pupil from ~17-meter length of channel, uncorrected for rain transmission. First return stroke.
Fig. 22. Flux at spectrograph entrance pupil from ~2-meter length of channel, uncorrected for rain transmission. First return stroke.
Fig. 23. Flux at spectrograph entrance pupil from 23-meter length of channel, uncorrected for rain transmission. First return stroke.
Fig. 24. Flux at spectograph entrance pupil from ~21-meter length of channel, uncorrected for rain transmission. First return stroke.
Fig. 25. Count 395, Storm 30 of the 1969 lightning study.