A High-Speed Time-Resolved Spectroscopic Study of the Lightning Return Stroke: Part I. A Qualitative Analysis

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ABSTRACT

The first time-resolved spectra of return strokes between the cloud and ground have been obtained. During the summers of 1965 and 1966 twenty-two spectra were obtained at the Institute of Atmospheric Physics, Tuscon, Ariz. The spectra were recorded with two high-speed streaking cameras converted to slitless spectrographs. The conversion was accomplished by mounting Bausch and Lomb replica transmission gratings in front of the cameras' objective lenses. The gratings are blazed for 5500 Å and have 600 lines mm⁻¹. Inverse dispersions from 70–140 Å mm⁻¹ were used. Most of the data were obtained with a Beckman and Whiteley high-speed camera. A 200-mm objective lens was used to focus the return stroke on a 0.5-mm horizontal slit. Thus, a 10-m section of the lightning channel was isolated for a discharge occurring at a distance of 4 km. Data have been obtained with a time resolution of 2–5 µsec. All spectra have been recorded on film calibrated for intensity and wavelength with a xenon source of known relative spectral emittance.

The following data have been obtained. Spectral emissions from 4000–6600 Å have been recorded with 10 Å wavelength resolution. All emissions have been attributed to neutral hydrogen or to neutral or singly ionized atoms of nitrogen and oxygen. No molecular or doubly ionized emissions have been identified in these spectra. The time for luminosity to rise from zero to its peak in a section of the channel is 10 µsec or less. Several faint lines due to neutral nitrogen and oxygen atoms persist for 150 µsec. The H-alpha line is present in these spectra. The recorded time sequence of spectral emissions from a section of the lightning channel is 1) line radiation from singly ionized atoms, 2) continuum, and 3) line radiation from neutral atoms. A flash has been recorded composed of at least 5 strokes. Two types of strokes are observed in this flash. The first type is characterized by intense short-lived emissions from singly ionized nitrogen atoms (NII) and a long lasting H-alpha emission. Continuum emission is relatively weak. In the second type, the singly ionized nitrogen emissions (NII) persist for a relatively long time and the H-alpha emission is very intense but short-lived. Continuum emission is relatively strong.

1. Introduction

The first time-resolved spectral studies of lightning strokes with both good spatial resolution and good temporal resolution have been obtained. A presentation and qualitative analysis of these data are reported in this paper, followed by a quantitative analysis in the next paper (Part II. A Quantitative Analysis).

The lightning discharge in its totality is called a flash which is composed of one or more strokes, consisting of a downward-moving leader process of low luminous intensity followed by an upward-moving return stroke of high luminous intensity. The first leader process usually involves a multi-branched stepped leader propagating downward until contact is made with the ground by some one branch. This particular branch then becomes the channel for the return stroke and the remaining stepped leaders merely become luminous branches. The luminosity of the return stroke lasts only a few hundred microseconds, the interval between the strokes being variable but most frequently being about 40 msec.

Slitless spectroscopy has been used in the study of lightning for many years, but never in a quantitative way until the present decade. Pickering (1901) was one of several early workers who published spectra of the lightning flash. Of the 15 or 20 publications falling in the interval from 1900–1960, the work by Israel and Wurm (1941), Dufay (1947), and Dufay and Tcheng (1949) deserves special attention. These papers represent the most thorough studies of the lightning spectrum available up to 1962. It is significant that previous to this date all publications on the subject dealt with the spectrum of the entire flash or a number of flashes. The first spectra of the flash resolved into its component strokes were reported by Salanave (1961). His data initiated a continuing series of papers on the physical properties of lightning as determined from spectroscopic analysis. For example, Prueitt (1963) obtained the first estimates of temperature within a stroke. This was followed by calculations of peak temperature (Uman, 1964), of mass density, electron density, pressure, and particle distribution for the same stroke (Uman et al., 1964a, 1964b). In addition, the electron density in lightning strokes was estimated from the broadening of the H-alpha line (Uman and Orville, 1964). The assump-

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tion of an optically thin emitting channel, necessary in most of the previous calculations, was checked and found to be valid for several strokes by examining the relative intensity from singly ionized nitrogen lines (Uman and Orville, 1965). An examination of the continuum radiation in the visible region indicated the continuum is probably not blackbody radiation or bremsstrahlung (Orville and Uman, 1965). All the foregoing analyses were performed on stroke-resolved spectra; that is, the lightning flash was time-resolved into its component strokes. The resulting exposure was an integration of all light received during the luminous phase from a section of the return stroke. All physical calculations therefore represented at best some kind of "average" applied to the luminous stage of the return stroke.

The desirability of time-resolving the lightning stroke, a luminous event lasting a few hundred microseconds, was recognized by several investigators. Israel and Fries (1956) constructed a scanning spectrograph with a time resolution of 20 μsec, but failed to obtain a spectrum. Vasy (1955) performed a series of laboratory experiments on the temporal characteristics of spectral emissions from sparks and intended to extend the techniques to lightning. A few years later Zhivlyuk and Mandelshtam (1961) were more specific in their objectives and stated, "at the present time we are setting up experiments on the measurement of the lightning temperature with time sweep." Private communication with Mandelshtam in 1966 confirms that these experiments were never performed.

The success in quantitative analysis of the integrated spectra of lightning strokes stimulated experiments designed to time-resolve the stroke itself. A time resolution of 20 msec had been obtained by Salanave et al. (1962) in recording the integrated spectrum of individual strokes, but an increase of three orders of magnitude was required to resolve the stroke on a microsecond scale. Krider (1965) reported the first time resolution of spectral emissions from individual return strokes using a photometric system with narrow passband interference filters. Although this was a significant step, it failed to isolate a narrow section of the lightning channel and yielded relative intensity measurements that were suspect. The problem of time-resolving the spectral emissions from a narrow section of the channel remained unsolved.

Experiments in our laboratory indicated a high-speed streaking camera with fast film should be capable of recording the spectral emissions from a section of the lightning channel with 5-μsec time resolution. The advantages of a photographic system include a high sensitivity and the possibility of recording simultaneously the intensities of many spectral lines. An additional advantage is that a permanent record in simple form is obtained. Among the disadvantages of film are the sensitivity variation with wavelength and the nonlinear response to light. Also, a careful calibration procedure and processing technique are required to minimize the errors in a photographic system. However, the advantages are more important than the disadvantages in a study of the lightning stroke; therefore, a high-speed streaking camera modified to a slitless spectrograph was used in the summer of 1965 to study the spectral emissions from a stroke. The initial success of this experiment was reported (Orville, 1966) and the experiment repeated in the summer of 1966. An analysis of all data from the two summers has been completed and is presented as Parts I, II and III in this issue.

2. Equipment

A high-speed streaking camera is required to time-resolve the lightning stroke spectrum. Slitless spectrographs used by Salanave et al. (1962) were of sufficient speed to resolve the spectrum of a flash into its component strokes on a time scale measured in milliseconds, but a high-speed camera is required to time-resolve the lightning stroke on a scale measured in microseconds, an increase of three orders of magnitude.

The slitless spectrographs used by Salanave isolate a 1-cm section of the channel in the focal plane, the image in the focal plane being focused on a film drum which spins at 1 rps. An increase of three orders of magnitude can be obtained by reducing the slit width by a factor of 10 and increasing the drum revolutions by a factor of 100. High-speed streaking cameras are uniquely designed for this task.

Figs. 1 and 2 illustrate two types of high-speed streaking cameras converted to slitless spectrographs. In Fig. 1 the light from a distant lightning stroke enters a prism-grating combination and is then focused on a slit which isolates a small section of the channel. The prism-grating combination is adjusted to produce a "straight-through" path for the first-order spectrum. From the channel isolator, the lightning spectrum is focused by a lens and swept by a rotating mirror along the circumference of a stationary film drum. The result is a time-resolved spectrum, the time resolution being determined by the time required to sweep the slit image on the film. Thus, a 1-mm slit image and a writing rate of 0.2 mm (μsec)^{-1} produce a time resolution of 5 μsec.

In Fig. 2 the input optics to the high-speed streaking camera are the same as in Fig. 1. The only difference in principle is that the mirror is fixed and the film drum is rotated to streak the spectrum. Once again, a time-resolved spectrum is obtained.

The advantage of a moving mirror is that higher time resolution can be obtained compared with a system having a fixed mirror and moving film. The necessity for mirror motion restricts the size of the mirror and thus severely limits the f stop of the camera. The size of the mirror can be increased, however, if the mirror is fixed and the film spins in a drum. This latter technique is preferred when the light source is faint and sufficient time resolution can be obtained with the spinning drum.
Two cameras were used in this experiment, representing the two types of high-speed streaking cameras available. One had a spinning mirror to obtain time resolution and the other a spinning film drum. A Model 104 high-speed streaking camera was obtained on loan from the Los Alamos Scientific Laboratory, N. Mex., and converted to a high-speed slitless spectrograph by the addition of a Bausch and Lomb replica grating. The grating is blazed for 5500Å and has 600 lines mm⁻¹. An Aero Ektar f/2.5 field lens with a focal length of 178 mm was mounted behind the grating to focus the spectrum on a horizontal slit with a vertical width of 0.5 mm (channel isolator). The slit can isolate a 10-m section of a cloud-to-ground stroke at a distance of 3.6 km. A three-faced mirror driven by a turbine sweeps the spectrum. Compressed air drives the turbine. Although the turbine is capable of 4000 rps, it was found that 50 rps was sufficient to produce 5-μsec resolution. The spectral inverse dispersion was 143Å mm⁻¹.

In addition to the Model 104 camera, a Beckman and Whitley Model 318 high-speed streaking camera became available in the late summer of 1965. The suitability of this camera for lightning studies became very evident and the camera was used exclusively in the summer of 1966.

Fig. 3 shows the camera converted to a slitless spectrograph and mounted on a portable table with accessory equipment. Mobility is essential when the field of view is approximately 10° and the location of a lightning discharge is unpredictable. The Beckman and Whitley camera is an electrically driven moving-film streak camera capable of writing at speeds up to 0.3 mm (μsec)⁻¹. A rate of 0.12 mm (μsec)⁻¹, corresponding to a film drum rotation rate of 138 rps, is adequate to provide 4-μsec resolution with a 0.5-mm slit. By decreasing the slit width from 0.50 to 0.25 mm, data with 2-μsec resolution can be obtained. The film strip in the drum is 87.6 cm long. Drum and film are rotated in an evacuated housing. This produces less drum and film temperature-rise during operation and resolution loss at the image plane caused by air turbulence is minimized. The camera was converted to a slitless spectrograph by adding a Bausch and Lomb replica grating similar to the one used on the Los Alamos Model 104. A 180-mm field lens focused the lightning spectrum on a horizontal slit with a vertical width (channel isolator) of 0.53 mm. This will isolate a 10-m section of the stroke channel at 3.4 km. The inverse spectral dispersion is 80Å mm⁻¹. In the summer of 1966, a 200-mm f/3.5 Takumar lens was used to produce an inverse spectral dispersion of 72Å mm⁻¹. The dispersion, it should be remembered, is an average value in the visible region. The “straight-through” prism-grating combination produces a dispersion in the focal plane which is slightly nonlinear due to the dispersion of the prism superimposed on the dispersion of the transmission grating.

3. Photographic technique

Recording the spectrum of lightning on a scale measured in microseconds requires special consideration of the common sources of error in photometric work.

"Reciprocity failure" is a term referring to the fact that different film densities are obtained when the in
tensity of a light source and time are varied to produce the same exposure. The important factor controlling the failure of the reciprocity law is the time rate of formation of the latent image (Mees, 1954, p. 205). Berg (1940) performed a series of experiments on reciprocity failure at high intensities and short exposures. He noted that the latent image is formed by an electronic and ionic process. For brief exposures, the processes are separated because the electrons are more mobile than the ions. The dominance of the electronic process over the ionic process becomes complete at approximately 40 μsec, and at shorter exposure times there is no reciprocity failure. Sauvenier (1963) has studied the reciprocity failure between $10^{-6}$ and $10^{-4}$ sec. He finds no reciprocity failure between $10^{-6}$ and $10^{-5}$ sec and only a slight failure in the range $10^{-5}$ to $10^{-4}$ sec. Berg's classic work and Sauvenier's results are supported by Dubovik's (1964, p. 358) recent studies.

All high-speed time-resolved lightning spectra were recorded with an exposure time $\leq 5$ μsec. Reciprocity failure can therefore be neglected if a calibration source is used with an exposure time $\leq 10$ μsec. A G.E. type 1531-A Strobotac unit with a xenon source was used to calibrate the film. This has an adjustable flash duration from 0.8–3.0 μsec and the latter setting was used for all calibrations.

Emulsion sensitivity is a function of the relative humidity (Mees, 1954, p. 128) and temperature (pp. 232–237). For this reason, all film was stored under identical conditions and exposed to the calibration source within a few days after each storm.

Experience obtained during the summers of 1961–1964 at the Institute of Atmospheric Physics indicated that a film emulsion with high sensitivity would be required to time-resolve the spectral emissions from a lightning stroke. Although slightly out of date, Pressman's (1962, p. 80) survey of films and developers for high-speed recording presents a thorough analysis of the possible combinations. High Speed Infrared, Agfa Isopan Record, Linagraph Orthochromatic, Tri-X, Plus-X, and Linagraph Shellburst films were initially tested for speed, gamma, fog, and wavelength sensitivity. The film speed was the determining factor. Agfa Isopan Record was selected for initial exposures despite its high background fog and lack of red extended sensitivity. This latter characteristic is necessary to record the H-alpha emission from lightning. The second choice was Linagraph Shellburst film with low background fog, high gamma, and extended red sensitivity. Agfa Isopan Record was used in the Los Alamos Model 104 camera and recorded the first time-resolved spectrum of a lightning stroke on 14 July 1965. Subsequent use of Linagraph Shellburst film resulted in complete failure due to the film's low sensitivity. All film was overdeveloped 50–100% in Kodak D-19 at 70F.

Kodak 2475 Recording film became available in the middle of the 1965 lightning season and was used exclusively after its high speed and red extended sensitivity were tested. It is a film with low resolving power, medium granularity, medium acutance, and an ASA rating of 1000.

Subsequent to the first success of 14 July, all lightning spectra were recorded on Kodak 2475 Recording film in the Beckman and Whitley Model 318 camera. It was concluded that this combination is the most sensitive photographic system for time-resolving the spectral emissions from a stroke.

Photographic film must be calibrated for its nonlinear
response to light. An acceptable process is to use a stepped slit mounted in front of the Strobotac calibration source. The stepped slit was constructed by Prueitt (1963) and consisted of steps passing known relative amounts of intensity. Since the time of exposure is constant, relative exposure changes are directly related to relative intensity changes. Therefore, density can be plotted as a function of exposure to produce a characteristic curve. Film, cut from the same roll exposed to lightning, was exposed to the standard source and developed with the film containing the lightning spectrum. In this way, density variations due to the developer temperature variations and aging were eliminated. The film was brushed continuously during development to minimize the Eberhard effect.

4. Presentation of data

A total of 22 spectra were obtained in the summers of 1965 and 1966. The low number is indicative of the unpredictable nature of the source. To record a spectrum, the lightning stroke should occur within 10 km of the instrument and within a 10° field of view. If these conditions are met a spectrum will be recorded, assuming of course, that the camera is loaded, running at the appropriate speed, and the shutter is open. Since a time exposure is required, only lightning strokes occurring at night could be recorded. The problem of obtaining properly exposed spectra from a source as unpredictable as lightning was a major obstacle in this experiment. The small number of data is consistent with the experimental problem encountered when working in the atmospheric laboratory.

Seven time-resolved spectra are reproduced in Figs. 4–8. All spectral emissions are from approximately a 10-m section of the lightning return-stroke channel. In both Figs. 4 and 6, two prints have been made from the same negative to accurately present the dynamic range of the recorded image. The spectra cover different ranges of the optical region because the fortuitous positioning of the lightning stroke relative to the slitless spectrograph determines the wavelength range recorded. The recorded spectra will now be examined.

Figs. 4a and 4b are reproductions from the first time-resolved spectrum obtained on 14 July 1965. An extensive qualitative and quantitative analysis of this spectrum has been completed. Several weak lines at 4650, 6158 and 6456 Å persist for approximately 150 μsec, but are not visible in the reproduced spectrum. All of the recorded emissions are from unresolved multiplets or
lines superimposed on a broad continuum. The unresolved multiplets are identified by the most intense line. For example, NII 4630 refers to the singly ionized nitrogen multiplet (NII) composed of six lines whose brightest line occurs at 4630 Å. A time scale in microseconds is provided with a somewhat arbitrary zero point, arbitrary in the sense that “time zero” refers to the time when spectral emissions are first recorded. A closer stroke would shift “time zero” to an earlier point in the life of the return stroke and a more distant stroke would only have the very intense luminosity recorded, thus shifting “time zero” to a later time in the history of the stroke.

All of the intense emissions are attributed to nitrogen atoms in the singly ionized state (NII) with the exception of OII occurring at 5179 Å. The identification of OII was made after attempting to calculate the temperature from the relative intensities of NII radiation at 5003 and 5179 Å. Two spectra yielded temperatures in the 40,000–70,000 K range. These values exceed the temperatures in the 20,000–30,000 K range reported in Part II and are only presented here to confirm the OII identification. The reason for the high temperatures is that the 5179 Å radiation had been attributed entirely to NII multiplets with an excitation potential of 30 eV. The contribution of OII with an excitation potential of 28.8 eV is also important and contributes to an erroneous temperature value.

It is evident in Fig. 4, and indeed in all spectra obtained, that the singly ionized species emit first, followed by continuum emission. Both types of radiation reach their peak luminosity within 10 μsec. This short time contradicts Kriders’ (1965) measurement. He used a photoelectric system with narrow passband interference filters to monitor the spectral regions of interest. A curious feature of these data is the long period required for the intensity of various spectral features to rise from zero to peak luminosity. For example, NII emissions required approximately 40 μsec to reach peak luminosity. Kriders (1965) correctly suggested that the length of this period depends on the apparent time required for the leading edge of the return stroke to traverse the particular length of channel section under observation. The spectrum reproduced in Figs. 4a and 4b is from a stroke 3 km or less from the observation point. The Los Alamos Model 104 camera was located 17 m above the ground and elevated 3.6°. Then at a distance of 3 km, a 10-m section of the channel is being observed approximately 200 m above the ground. If the return stroke velocity is $3.5 \times 10^8$ cm sec$^{-1}$ (Malan, 1963, p. 25), the leading edge of the return stroke is propagated across the section of the channel under study in about 0.3 μsec. Therefore, the contribution to the rise-time made by the propagation of the return stroke is considered negligible in these data. Current rise-times to towers, power lines and captive balloons indicate a range of 1–15 μsec with 2.5 μsec the most frequent value for the first stroke (Schonland, 1956, p. 605). Subsequent strokes have current rise-

Fig. 6. Streaked spectrum from the first return stroke in a flash composed of five or more strokes. a. Dark print does not record the continuum present in the negative. b. Print from the same negative reproduced in Fig. 6a shows continuum and persistent H-alpha line.
times frequently too fast to be accurately measured. Berger and Vogelsanger (1965) indicate it is usually less than a microsecond and may be less than a few tenths of a microsecond. The spectral luminosity rise-time of 10 μsec or less is consistent with these results, but the comparison between cloud-to-ground lightning and strikes to towers, etc., may not be valid. Current rise-times are measured at the ground and spectra are obtained from a section of the return-stroke channel above the ground. It is apparent, as Krider (1966) has stated in a recent article, that he examined a large vertical section of the channel and consequently found long times for the intensity to rise from zero to peak value, the long times being due to the propagation time of the return stroke.

Fig. 5 is a spectrum from a one-stroke lightning flash recorded on 2475 Recording film. The wavelength and time scales are similar to Fig. 4 but several new features are apparent. Kodak 2475 film with its red extended sensitivity has recorded for the first time the emission at 6563Å from the H-alpha line in the Balmer series of hydrogen. The time characteristic of this emission is distinctly different from the NII and continuum emissions. The H-alpha peak emission follows by tens of microseconds the peak emissions of NII and continuum radiation. The H-alpha line was not present in Fig. 4 because the film (Agfa Isopan Record) was not sensitive to the 6563Å emission. This new feature is therefore a result of changing films and does not represent a physical difference between the strokes presented in Figs. 4 and 5.

Two other new features do represent a physical difference between return strokes. There is a dip in the continuum intensity at approximately 20 μsec and a short streak of light appears at approximately 10 μsec between 5003 and 5179Å. A similar feature appears to the right of 5680Å. These features can be related in the following way. The dip in the continuum is reminiscent of the luminosity variations within a section of the return-stroke channel first reported by Malan et al. (1935) and analyzed in detail by Malan and Collens (1937). They observed that a luminosity enhancement sometimes occurred between 10 and 50 μsec. The effect of the enhancement is to produce an “intensity dip” or local minimum. Malan and Collens examined the luminosity enhancements and associated them with current variations in the channel arising from branches supplying charge to the channel. They observed luminosity enhancements when the upward-moving return-stroke luminosity reached a branch point. This increase of luminosity was believed to be the result of increasing current due to the availability of another current source, the branch, and the increasing “freshness” of the charge left by the leader process.

It therefore appears that the continuum enhancement is the result of a branch point existing above the section of channel under study. Evidence of a branch appears
in the small streak of light previously mentioned between 5003 and 5179 Å. This streak of light is the 5003 Å emission from a branch. As mentioned previously, a similar emission appears to the right of 5680 Å. Recall that it is a property of slitless spectrographs that a change in the physical position of the source changes the position of the spectrum in the focal plane. Thus, emissions from a branch displaced to the right or left from the main return-stroke channel will have the branch spectrum displaced to the right or left of the spectrum produced by the main channel.

I conclude that the return-stroke luminosity reached a branch point approximately 5 μsec after propagating along the vertical channel section under study. The luminosity then traveled down the branch and at 10 μsec passed the isolated branch section, emitting intense spectral lines in the 5000 and 5680 Å regions. Less intense emissions were not recorded. The effect of tapping a new current source appears as an increasing luminosity in the main channel at approximately 30 μsec. Similar enhancements in the continuum intensity occur in three other time-resolved spectra and are probably associated with branch points above the channel section being studied.

Figs. 6, 7 and 8 present the first time-resolved spectral emissions from a multi-stroke flash. A total of five strokes were recorded of which the three most intense are reproduced. There is reason to believe that the order in which the strokes are presented is the order in which they occurred. The ambiguity of stroke order arises because the film strip is rotating at about once in 10 μsec and the strokes are separated by tens of milliseconds.

Fig. 6 is believed to be the first stroke in the flash because the spectrum of a branch has been obtained. Fig. 6 is divided into parts a and b to reproduce the exposure latitude contained in the negative. Just to the left of 5680 Å there is an unidentified emission which appears for 5 μsec or less. This unidentified emission is more obvious in Fig. 6b than in 6a. Similar emissions occur to the left of 5942 Å. The emissions in the 5942 Å region are actually composed of two lines 10 Å apart. In Fig. 6b these lines are not resolved because of overexposure, but to the left of 5942 Å there are two lines faintly resolved. These faint lines are the 5932 and 5942 Å emissions from a branch in the return stroke. Since it is the first stroke which characteristically exhibits branching, I conclude that Fig. 6 is the first stroke in the flash.

The spectrum in Fig. 6 contains the characteristic NII lines identified in previous spectra. NII lines with the lowest excitation appear first followed by lines with a higher excitation potential. Thus, NII 5680 (20.6 eV) appears before NII 5942 (23.2 eV) and lasts longer. The time of continuum emission is best represented in Fig. 6b. The distinctive H-alpha line is absent or very faint in the first few microseconds, but quickly becomes very intense and decays slowly relative to the other emission species. H-alpha emissions are recorded beyond 160 μsec.

Fig. 7, believed to be the second stroke in the flash, exhibits several characteristics different from the first stroke. Since there is no evidence of the branching found in Fig. 6, it appears this is a subsequent stroke to the first one. Norinder and Dahle (1945) found in flashes with 4–7 strokes that the second or third strokes usually had the highest magnetic flux density and presumably the highest current. It is reasonable to assume that the highest current would be associated with the highest luminosity. Therefore, I conclude that Fig. 7 is probably the spectrum of either the second or third stroke in this flash.

In Fig. 7 all NII emissions and the continuum last longer relative to similar emissions in the first stroke reproduced in Fig. 6. Continuum emission is also more intense at longer wavelengths and cannot be explained by an increase in the film sensitivity or optical effects such as vignetting. The H-alpha emission is overexposed and decays quickly until, beyond 120 μsec, emissions are no longer recorded. A water vapor absorption band in the 5942 Å region is very evident in the strong continuum radiation. Weak absorption bands in the 6260 Å region are apparent and are unidentified. They were first reported by Wallace (1964).

Fig. 8 is a reproduction of the third most intense spectrum in the flash. It may have been the third stroke in the flash. The NII emissions are very brief and the Halpha emission lasts for more than 160 μsec. The overall intensity is less than Fig. 6, but the time characteristics of the emissions are very similar. The remaining two strokes in this flash were much less intense and are not suitable for reproduction. However, the spectral emissions in the two remaining strokes are similar to Fig. 8, albeit very faint, and the H-alpha emissions are recorded for approximately 500 μsec, or 0.5 msec in each stroke.

It is indeed unfortunate that the current is unknown in the flash components reproduced in Figs. 6, 7 and 8. Two distinctive types of strokes emerge from this example. In the first type we have the intense short-lived emissions of NII followed by a long lasting H-alpha emission. Continuum emission is relatively weak. In the second type, we note a high intensity stroke at all wavelengths (5680–6600 Å). The NII emission persists for a relatively long time and the H-alpha emission is intense but short-lived. Continuum emission is relatively strong.

It is interesting to consider several differences between the time-resolved slitless spectrograms of lightning reported in this paper and the slit spectrograms obtained by Wallace (1964). Wallace's spectra represent the most complete compilation of wavelength identifications in the lightning spectrum. A significant difference between the time-resolved data and Wallace's (1964) data is the relative brightness of the emissions in the 5680, 5942 and 6163 Å regions. In the time-resolved data (Fig. 6) we note relatively intense emissions in the 5600 and 5942 Å regions and a weak short-lived emission at 6163 Å. An examination of the original nega-
tive indicates the apparent short-lived emission at 6163Å persists as a faint line beyond 100 μsec. The short-lived emission is due to NII and the persistent faint emission is probably OI. In Wallace’s (1964) data, the 5680Å emissions are weak, the 5942Å emissions are completely absent, and the 6163Å emission is relatively bright.

There are several possible reasons for these differences. The spectrographs and films used in the two separate experiments may have different sensitivities as a function of wavelength and this may account for all the differences noted above. On the other hand, the characteristic emission times of species within the lightning stroke can be used to explain the qualitative differences between slitless spectra and slit spectra. It has already been observed that the emission in the 6163Å region on time-resolved slitless spectra is composed of a short-lived NII emission followed by a faint persistent OI emission. On a slit spectrum, however, the total amount of light would be integrated, to give the effect of an intense line. Wallace (1964) observed a strong line in this region. In the 5680 and 5942Å regions the emissions are attributed solely to NII emissions which occur for a relatively short time, on the order of 20 μsec. In Wallace’s data the 5680Å emission appears as a weak line and the 5942Å emission is absent. A slit spectrograph time-integrates the light from a flash and therefore favors the lines with a persistent emission. (This is particularly evident in the strong H-alpha emission recorded by Wallace.) It seems reasonable that the 5680Å emissions appear as weak lines in Wallace’s data. The absence of the 5942Å emission has been suggested by Wallace (private communication) as due to a strong continuum radiation recorded in his spectra which makes it difficult to discern the 5942Å emissions and to a moderately strong water vapor absorption line at 5942Å. It appears, therefore, that a short emission time, a relatively high continuum, and a water vapor absorption band may be sufficient to explain the absence of the 5942Å emission in Wallace’s data.

5. Microphotometer traces

To complete the qualitative analysis and take the first step toward quantitative analysis, it is necessary to obtain microphotometer traces. These traces represent percent transmission through the film emulsion as a function of wavelength. They must be corrected by a tedious process to obtain relative intensity. It is sufficient to examine the uncorrected traces over most of the

![Fig. 9. Microphotometer traces in the blue region of the optical spectrum up to 25 μsec. Traces are presented every 5 μsec and are uncorrected for the nonlinear response of the film emulsion.](image)

![Fig. 10. Traces presented in Fig. 9 are continued to 50 μsec.](image)
spectrum to point out several important qualitative features.

In Figs. 9 and 10 the traces from a time-resolved spectrum of a lightning stroke are presented to 50 μsec in increments of 5 μsec. They were obtained by tracing across a time-resolved spectrum every 5 μsec. The spectrum from which these traces were obtained is not reproduced in this paper. The wavelength identifications have numbers associated with them which refer to multiplets of the particular species. Thus, NII (5) 4630 indicates that the unresolved NII lines at 4630 Å compose the fifth multiplet of singly ionized nitrogen according to the tables of Moore (1945). Multiplet designations are a convenience and are frequently included in wavelength identifications.

As previously noted in reproductions of time-resolved spectra, NII lines are dominant. An OI line appears at 4368 Å in the first 5 μsec. Compare OII 4349 and OI 4368 and note that OII 4349 is initially the most intense line, but as time increases to 20 μsec the OI 4368 line becomes stronger relative to OII 4349. This is entirely consistent with a cooling channel that was initially dominated by radiation from singly ionized species. Beyond 25 μsec the singly ionized nitrogen lines blend into the continuum until only NII 4630 is recognizable at 50 μsec. The upper excitation potential of NII 4630 is 21.1 eV and lower than the excitation potential of adjacent NII lines. Thus, we are not surprised to see its relative persistence.

In Figs. 11 and 12, microphotometer tracings from 4500–6000 Å are presented up to 50 μsec. This set of tracings was obtained by microphotometering every 5 μsec the spectrum reproduced in Fig. 4. Note how quickly the unresolved 5179 Å lines decrease with time until they blend with the continuum between 20 and 25 μsec. This behavior is representative of emission lines originating from the high excitation potentials in the NII and OII atoms (~30 eV) as compared to the lower excitation potentials whose lines such as 5000 Å (~23 eV) persist for 50 μsec. The shape of the 4630 multiplet changes with time as the NII radiation decreases and OI emissions in the 4650 Å region increase. The profile of the “uncontaminated” 4630 multiplet can be estimated by plotting the gf values of the component lines, where g is the statistical weight of the lower level and f is the absorption oscillator strength [see, for example, Uman and Orville (1964b)]. A change of the profile with time indicates the qualitative effect of the OI emissions at 4650 Å. In the 5080 Å region the intense NII emissions are overemphasized by the sensitivity of Agfa Isopan Record film.

The last set of microphotometer tracings covers the interesting H-alpha region. In Figs. 13 and 14 the region
from 6450–6650Å is presented. These tracings were obtained from the spectrum reproduced in Fig. 6. Note in the first 5 μsec an unidentified line appears just to the left of 6563Å. This line is the NII 6611 emission from a branch. The presence of the branch spectrum was previously treated under a discussion of Fig. 6. As several spectra have previously indicated, the H-alpha emission is initially very weak relative to the NII emissions. Beyond 15 μsec the H-alpha line dominates the spectral region and the NII lines disappear. Fig. 6 indicates significant H-alpha emissions are recorded beyond 160 μsec.

6. Summary

A 10-m section of the lightning stroke has been isolated and the optical spectral emissions streaked in time. These first time-resolved spectra indicate all initial emissions are due to singly ionized species of nitrogen and oxygen. These emissions and the continuum radiation reach peak luminosity within 10 μsec. Singly ionized lines with the lowest excitation potential appear first followed by lines with a higher excitation potential. Continuum emission reaches peak luminosity after the singly ionized species and before the radiation from neutral species. Several faint lines due to neutral nitrogen and oxygen atoms persist for approximately 150 μsec.

The emission features of H-alpha are distinctly different from the emissions of the singly ionized species. In the first 5 μsec the H-alpha line is very faint or completely absent in the spectrum. Its intensity rises relatively slowly and clearly peaks after 10 μsec, decaying until it is one of the few lines detected in the visible spectrum beyond 100 μsec.

Spectra from a flash composed of at least five strokes have been obtained. The spectra fall into two types. In the first type, four of the five recorded spectra exhibit relatively short-lived NII emissions and a long lasting H-alpha emission. The continuum emission is present but relatively weak. On the other hand, the remaining spectrum and second type shows NII emitting for a relatively long time compared to the same emitting species in the first four spectra. The H-alpha emission is very intense but short-lived. The continuum emission is more intense. Thus, Type I exhibits short-lived NII emissions, long lasting H-alpha emission, and a
weak continuum. Type II has long lasting NII emissions, an intense short-lived H-alpha emission, and a strong continuum.

A quantitative analysis of these data is presented in the next paper.

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