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The Optical Spectrum of Lightning

A revival of the spectrographic study of lightning may help solve some outstanding puzzles in cloud physics.

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Although a great deal of attention has been given to the mechanisms of charge generation and lightning, there still exists much uncertainty about the details. It is reasonable to expect that with improved observational techniques it should be possible to learn more about the nature of the processes involved. In this connection a detailed knowledge of the physical conditions surrounding the lightning discharge assumes considerable importance.

A large amount of work has been done on the long-wavelength (radio) region of the lightning discharge spectrum; this has obvious applications to communications and the detection of nuclear explosions, in both of which lightning produces interference. Also, much work has been done on the direct photography of lightning (especially with the Boys camera), to obtain time resolution.

Comparatively little use has been made of the optical spectrum. It has always been obvious, of course, that this spectrum must resemble that of the ordinary spark in air, but even here there are some interesting differences which require explanation. In this connection it should be noted that the energy of the discharge is extremely large: Potential differences of the order of 1 billion volts produce pulsed currents of 50,000 amperes and more, each pulse lasting only a few milliseconds. It is common for a flash to consist of a dozen or more such pulses, or "strokes." It is not surprising, therefore, that the spectrum has some interesting features—shared by some of the plasma phenomena which are of such wide interest in contemporary physics.

During the summer of 1959 I was impressed by the brilliant, vertical flashes of lightning which occurred with almost clocklike regularity over the Santa Catalina Mountains in southwestern Arizona. It seemed evident that interesting spectra could be obtained by placing a prism or grating in front of an ordinary camera lens in such a way that the direction of dispersion was horizontal. This is merely an extension of the objective prism technique long used by astronomers in the study of meteors, comets, and sharp-emission nebulae.

The lightning flash has been an object of spectroscopic analysis for almost 100 years, but the literature is not extensive, and surprisingly little research seems to have been done in view of the great amount of information that can usually be expected from spectrum analysis of an optical phenomenon. In a thorough search of the literature I found only 19 references to research done since 1900 that involved the photographic observation and interpretation of lightning spectra. In these investigations the equipment has generally been adapted from pre-existing instruments—usually fast, low dispersion slit spectrographs used by astronomers to study auroras, nebulae, and other faint sources. This equipment has enabled the observers to record the lightning spectrum by way of the general illumination on clouds but not in the stroke directly; it would be extremely unlikely that a lightning stroke could be imaged on the slit of a conventional spectrograph. This situation can be partially circumvented by using a *slitless* spectrograph, but even less use has been made of this instrument than of the other (*1*). The especially favorable characteristics of "blazed" diffraction gratings, which combine good illumination with high dispersion and resolution, open up wide possibilities in slitless spectroscopy.

Survey of Observations, 1901–1960

At the beginning of the century Pickering (*2*) at Harvard Observatory and Fox (*3*) at Chicago secured the first slitless spectra of lightning. In 1905 Larsen (*4*) published two spectra he obtained with a small prism in front of an ordinary hand camera. The first slit spectra were secured in 1917, when two spectrograms were obtained by V. M. Slipher (*5*) at the Lowell Observatory. The knowledge of spectra at that time was sufficient to provide some chemical identifications, but not to yield information on the physical processes involved.

From 1923 to 1925 J. Dufay (*6*) obtained 14 slit spectra covering the region from 2800 angstroms to H-alpha. Molecular bands attributed to N_2 were added to the list of atomic nitrogen and oxygen lines already known from the work of Slipher. At this time the quantum-mechanical

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theory of spectra was just emerging. Energy-level diagrams, excitation potentials, and related tools of spectrum analysis were only newly developed and were not immediately applied to working out the energy levels in the lightning discharge.

In 1941, Israel and Wurm (*7*) obtained nine slitless spectograms, but only the best one was studied at that time. They classified the lines into multiplets, with corresponding excitation potentials, and hence were able to arrive at some notion of the energy involved in the discharge. The lines of N II, which are the most prominent features of slitless spectra, typically have upper excitation potentials around 20 electron volts, or 34.5 electron volts above the ground state of N I. As a result of their analysis, Israel and Wurm were the first to report that the degree of excitation increases from the cloud toward the ground. In a later publication (*8*) Israel and Wurm presented analyses of five spectra they had secured in 1941. The most interesting feature of this work seems to have been the discovery of emissions due to ionized calcium at the base of a stroke which hit the ground about 2 kilometers from their camera.

Table 1. Census of published observational material.

Classification	Spectra (*N*)
1) Slit spectra	
a. From the ultraviolet, through the visible, to Hα (1917–60)	34
b. In the red and near infrared, as far as 9000 A (1950–52)	5
2) Slitless spectra	
a. Early observations (1901–05), before an adequate theory of spectra had been proposed	17
b. Later work (1941–49), subject to interpretation in terms of excitation along the discharge	7

In 1943 Nicolet (*9*) published a revision of Slipher's list of lines and classified them according to multiplets.

In 1947 and 1949, J. Dufay and M. Dufay, with T. Mao-Lin (*10, 11*) published what is, even today, the most comprehensive study of the lightning spectrum in the range from 2950 A to H-alpha. The region above 3838 A was studied on ten spectrograms; below this wavelength the analysis rested on a single spectrum. Also in 1949, the Dufays (*12*) published the results of studying an exceptionally good slitless spectrogram. It was obtained with a 60° prism in front of an F/4.5 lens of 8-centimeter aperture; the dispersion was 44 angstroms per millimeter at 4000 A. From photometer tracings of this spectrum, whose hydrogen lines were assumed to be broadened by the Stark effect, the intermolecular field was estimated to be of the order of 20,000 to 40,000 volts per centimeter, and the ratio of ionized to neutral particles was calculated to be 5×10^{-4}. The findings confirmed the observation of Israel and Wurm that the excitation increases toward the ground.

During the years from 1950 to 1952, fast slit spectrographs of low dispersion were used to extend observations into the near infrared as far as 9078 A. The work of Jose (*13*), Petrie and Small (*14*), and Knuckles and Swensson (*15*) produced a total of five spectrograms. Lines due to neutral argon were found by Petrie and Small.

In 1959, L. Wallace (*16*) obtained an excellent slit spectrogram in the region from 3670 to 4280 A, using an auroral grating spectrograph with a dispersion of 22 angstroms per millimeter. Most recently, Hu Ren-Chao (*17*) published a report on the study of seven split spectra taken with an auroral spectrograph. The instrument was provided with a grating and gave a dispersion of 100 A/mm over an interval of 1500 A. In a series of hour-long exposures Hu Ren-Chao and his associates covered the region from 6563 A (Hα) to 2811 A, in which range they found 200 emission lines and band heads. This investigation also included a comparison between lightning and spark spectra.

A census of the published observational material is shown in Table 1. Note that the important information to be expected from studies under the classification 2*b* has been based upon a relatively small number of spectra.

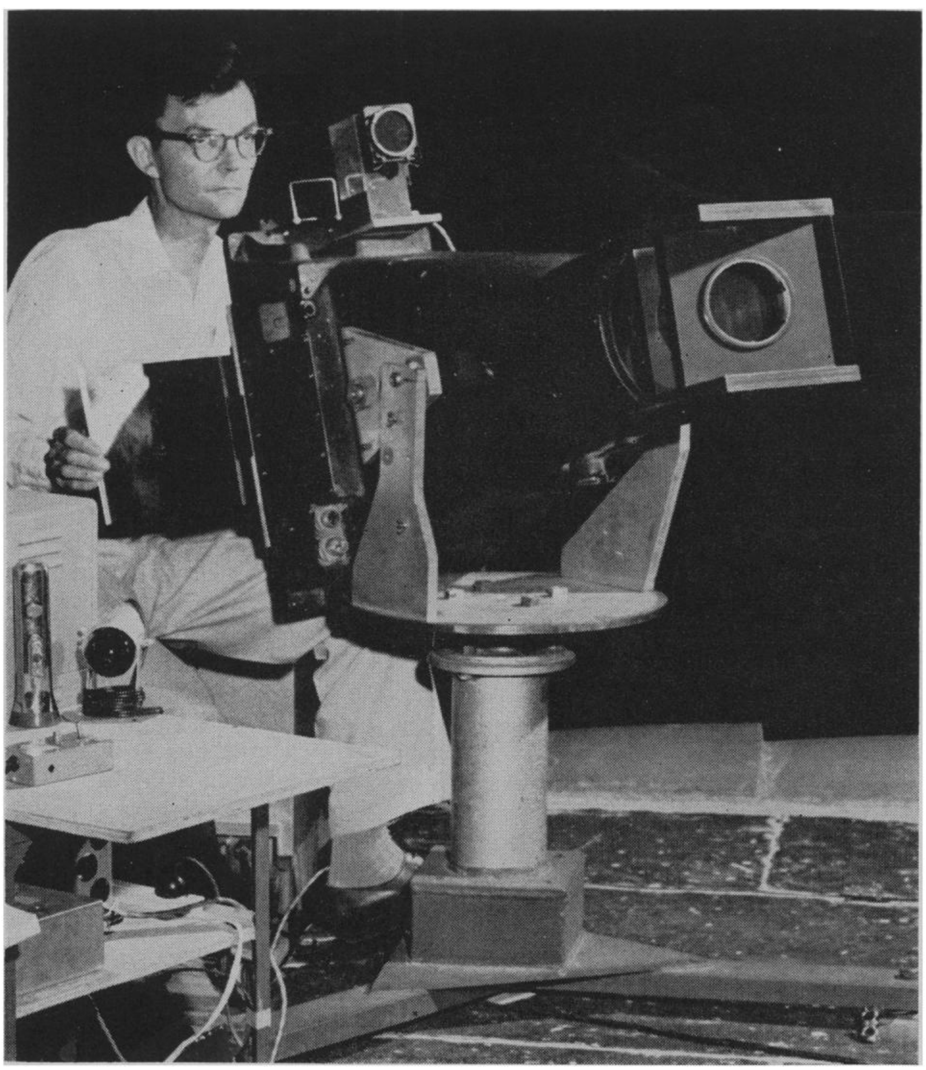

Fig. 1. Lightning spectrograph in use. The dark-slide is drawn from in front of the 8- by 10-inch film holder and then closed when a bright flash appears in the view finder. The prism-grating assembly is shown attached to the front of the K-18 aerial camera. [Bob Broder, University of Arizona Press Bureau]

Aerial Camera Fitted with Diffraction Grating

Under the joint sponsorship of the University of Arizona's Applied Research Laboratory and Institute of Atmospheric Physics, a number of good spectra were obtained in a pilot investigation during the summer of 1960.

The instrument consisted of a K-18 Aero-Tessar camera modified to use 8- by 10-inch Eastman Royal Pan cut film and equipped with an objective prism-grating combination (see Fig. 1). The prism and grating are arranged so that their respective deviations counterbalance, to make a more "straight-through" optical system. The system aperture is 8 centimeters, and the focal length is 60 centimeters. The spectra obtained have a normal dispersion of approximately 25 A/mm in the first order. The grating is a Bausch and Lomb transmission replica, blazed for 5500 A and giving bright spectra in a region for which the lens is well corrected—that is, from 4000 to 6000 A.

Direct photographic copies of slitless spectra obtained elsewhere are not available, so detailed comparison of our results with other work is not possible. However, the superior optical specifications of the present equipment make it clear that greatly improved resolution can be expected. That this is in fact the case is especially well shown by the resolution of a pair of lines at 5001 and 5005 A (N II) and by several sharp, faint lines near the strong N II line at 4630 A (see Fig. 2). The hydrogen line, H-beta, appears very much broadened, and its intensity varies from one spectrum to another. The atomic hydrogen is, of course, derived from the dissociation of water vapor in the discharge.

During the period from 21 July to 8 October 1960, 97 films were exposed during 13 successive storms. On these films appear 14 good grating spectra, comparable to those shown in Figs. 3 and 4. There are 19 of inferior quality, not suitable for detailed analysis but probably useful for purposes of classification and statistical study. All the films have been impressed with spectrum-densitometer standards. In addition, there are ten well-exposed prismatic spectra, produced by strokes fortuitously imaged by the prism and the zero order of the grating. They are of very low dispersion and hence are unsuitable for a detailed study of individual lines, but the relation between intensity and wavelength at selected points along these spectra should be significant. This is particularly true with respect to the streaks of continuous spectrum at isolated points (so-called "beads") along the discharge channel. It is important to determine whether these "hot spots," as I call them, are merely places where there is an over-

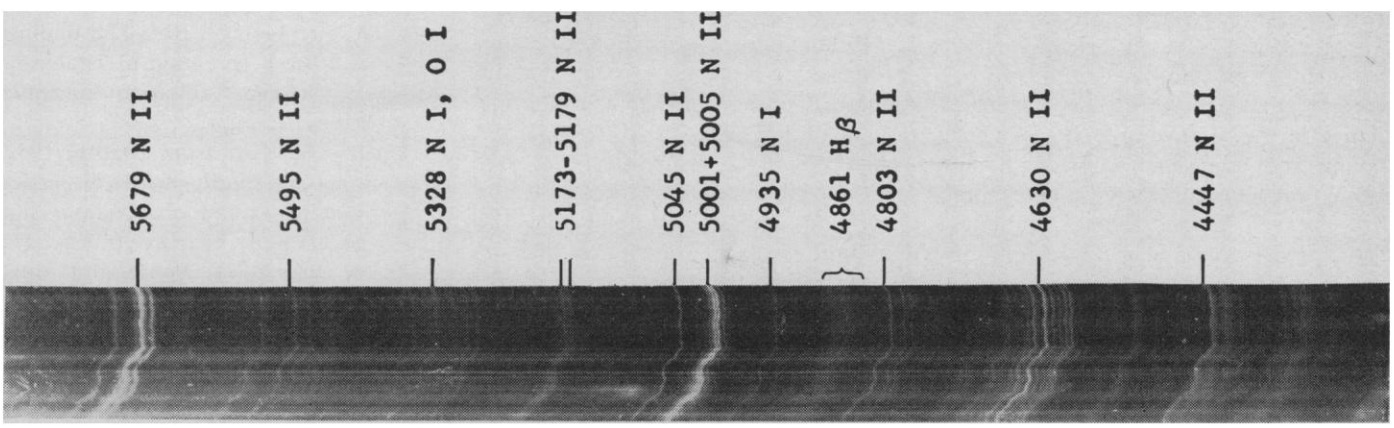

Fig. 2. Enlarged section of slitless spectrogram of lighting, with a representative group of lines identified. The photograph is oriented with the shorter wavelengths to the right, to match the orientation of the spectra in Figs. 3 and 4.

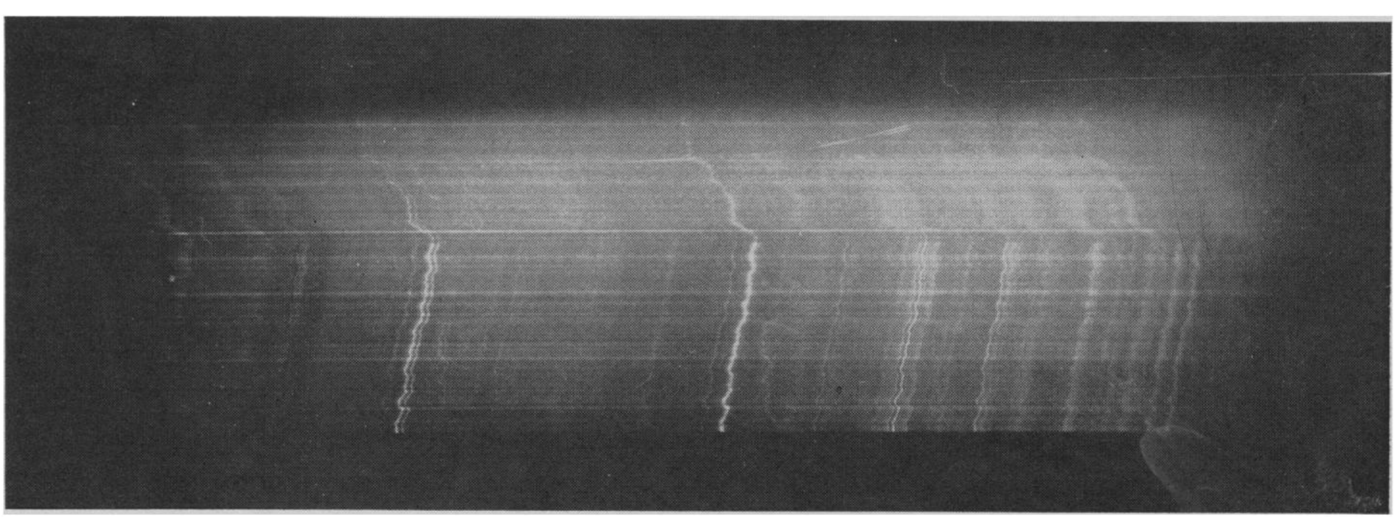

Fig. 3. Slitless spectrogram of lightning, focused for the green-yellow region. The spectrum extends from 6200 A on the left to 4000 A on the right. The bright central line is the 5001- to 5005-A pair (N II); the intense line at the left is 5679 A (also N II). Note the conspicuous absorption band (H_2O) between 5900 and 6000 A.

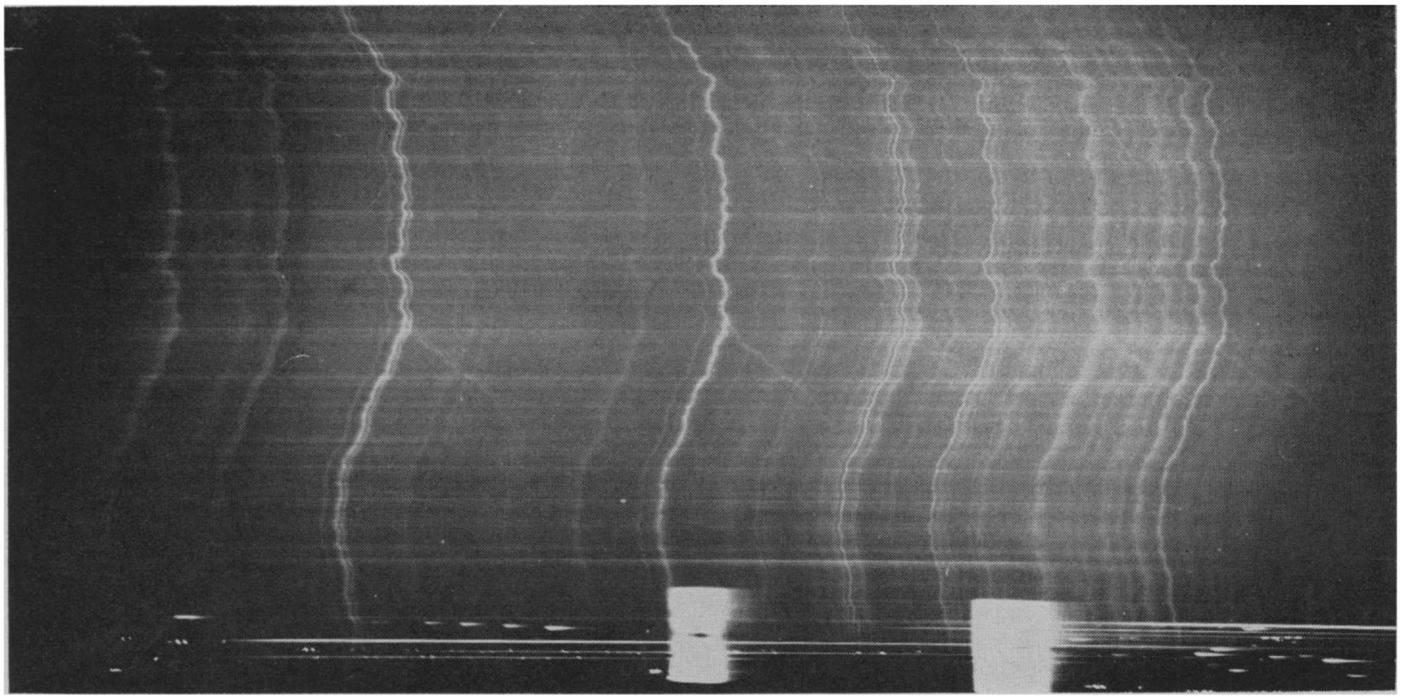

Fig. 4. Slitless spectrogram of lightning, focused for the blue-violet region. The last strong line on the right is 3995 A (N II). The bright line in the center is the 5001- 5005-A pair (also N II). Much fainter lines are visible farther to the violet, down to about 3800 A. The sharp drop-off in intensity of the spectrum in the ultraviolet is due to absorption in the glass optics.

exposure due to chance orientation of the channel in the line of sight, or whether they represent an intrinsic change in the relative amounts of continuous and bright-line emission. Israel and Wurm noted an increase of excitation at such points. These continua, if real, may correspond to regions of immense magnetohydrodynamic forces, as the huge current flows around sharp bends in the channel.

Preliminary Findings on New Spectral Photographs

At the time of this writing, only the region from about 4000 to 5500 A has been studied in detail, on two of the best grating spectra. However, it is already clear that the great majority of lines can be assigned to N II, with lesser numbers assigned to N I, O II, and O I, in that order.

On one strongly exposed spectrum a faint line at 4806 A has been tentatively associated with ionized argon. This line has not been found on other spectra so far examined; if confirmed it will be the first identification of A II in the lightning spectrum. The 4806-A line is the strongest member of the $4s^4P$–$4p^4P^0$ multiplet; there is no indication of a somewhat weaker line at 4736 A, belonging to the same multiplet.

The variation in the intensity of H-beta is very interesting. On the basis of a preliminary examination of a few of the better spectra, it seems that its strength is proportional to the intensity ratio 4935 A (N I) to 5045 A (N II).

A qualitative comparison of our spectra with laboratory spectra of the spark and arc in air shows that the lightning spectrum resembles that of the arc rather than that of the spark. Evidently the high current density is more significant than the high potential in fixing the prevalent state of ionization. This circumstance will explain an observation by A. Vassy (*18*) that the lines of N III and O III appear in the spectrum of long sparks but not in lightning.

A wide absorption band, extending from approximately 5900 to 6000 A, shows clearly in the more strongly exposed spectra (see Figs. 3 and 4). This band is due to water vapor in the intervening air path, as was first suspected by Dufay (*11*) and later confirmed by Hu Ren-Chao (*17*).

No emission features have been found which can be attributed to molecules. In fact, a search has been made to confirm the occurrence of band heads in the systems of N_2 and N_2+, noted by Israel and Wurm and by Dufay in their slitless spectra. The result has been negative. The absence of molecular bands in slitless spectra is not surprising when one considers that here, as Vassy (*18*) pointed out in 1954, we have the spectrum of only the violent principal discharge, characterized by intense ionization. The slit spectra, on the other hand, represent multiple exposures, from reflections by clouds, of light from both the principal discharge and the afterglow. It is in the latter source that molecular bands can be emitted. To judge from the published tracing of Wallace's spectrum (*16*), this is very definitely the case.

Notes added in proof: 1) On a slitless spectrum obtained 23 June 1961, in Tucson, the N_2 and CN bands between 3850 and 3914 A appear very strong, while the 3995 line of N II is comparatively weak. A re-examination of the spectra from the 1960 season has shown that these molecular bands have indeed appeared faintly in several instances, but it is clear that this most recent spectrum is quite unusual. No explanation of this apparent anomaly is forthcoming at the moment.

2) In the Russian news magazine *Krasnaya Zvezda* (issue of 3 June 1961) it is stated that Y. Zhivlyuk and S. Mandel'shtam have determined the temperature of lightning discharges to be about 20,000 degrees from slit spectrograms taken in 1958. [See also *J. Exptl. and Tech. Phys. U.S.S.R.* **13**, 338 (Aug. 1961)]. It is interesting to compare this determination of temperature with that of Wallace, given in his 1960 paper. The latter used the N_2+ bands around 3825 and 3900 A, and obtained temperatures ranging between 30,000

and 6000°K—depending upon how much allowance was made for overlapping by the CN band near 3825 A!

3) On 17 August 1961 the first *time-resolved* spectra of lightning were obtained in Tucson, with a drum camera attached to the spectrograph described in this article. Spectra of the brighter components of multistroked flashes are separated, rather than superimposed. Some of these spectra are superior in detail to any obtained heretofore. In certain cases the spectrum of the afterglow has been separated from that of the principal discharge.

References and Notes

1. In slitless spectroscopy a line-like source acts as its own slit and collimator when placed at a considerable distance from a camera equipped with an objective prism or grating. The resulting spectrum is really a series of monochromatic images of the entire *source* (rather than of a slit, as in conventional spectroscopy). By noting the relative widths and intensities of selected "lines" at various positions in the source, one often can infer a good deal about the distribution of temperature, pressure, and ionization.

2. E. C. Pickering, *Astrophys. J.* **14**, 367 (1901).
3. P. Fox, *ibid.* **18**, 294 (1903).
4. A. Larsen, *Smithsonian Inst. Publs. Ann. Rept.* (1905), p. 119.
5. V. M. Slipher, *Bull. Lowell Observatory No. 79* (1917).
6. J. Dufay, *Compt. rend.* **182**, 1331 (1926).
7. H. Israel and K. Wurm, *Naturwissenschaften* **29**, 778 (1941).
8. ——, *Wissen. Abhandl. deut. Meteorol. Dienstes in franz. Besatz* **1**, 48 (1947).
9. M. Nicolet, *Ciel et terre* **59**, 91 (1943).
10. M. Dufay, *Compt. rend.* **225**, 1079 (1947); J. Dufay and T. Mao-Lin, *Compt. rend.* **228**, 330 (1949); M. Dufay, *Ann. géophys.* **5**, 255 (1949).
11. J. Dufay and T. Mao-Lin, *Ann. géophys.* **5**, 137 (1949).
12. J. Dufay and M. Dufay, *Compt. rend.* **229**, 838 (1949).
13. P. D. Jose, *J. Geophys. Research* **55**, 39 (1950).
14. W. Petrie and R. Small, *Air Force Cambridge Research Center Rept. No. AR-6* (1951).
15. C. F. Knuckles and J. W. Swensson, *Ann. géophys.* **8**, 333 (1952).
16. L. Wallace, *J. Geophys. Research* **65**, 1211 (1960).
17. Hu Ren-Chao, *Sci. Record (China)* **4**, 380 (1960).
18. A. Vassy, *Compt. rend.* **238**, 1831 (1954).

Federal Support of Research Careers

Government joins universities to increase the number of career appointments in research.

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For some years it has been evident to qualified observers that the absence of adequate numbers of stable career opportunities for scientists has been an increasingly important barrier to the establishment of a sound research structure for the nation as a whole.

During and since World War II, university research in the United States has been heavily dependent for support upon federal grants and contracts. This support is often, although not always, provided for long periods of time. In many fields of science, support for research has grown at a pace exceeding the capacity of universities to staff the programs from their regular sources of income. The staffing problem has been solved in various ways. Large research organizations have been set up outside universities. Government laboratories have been expanded. Finally, universities have adopted practices enabling them to undertake larger research programs without committing a correspondingly larger proportion of university funds. These practices have included such steps as payment of the salaries of faculty members and other professional people from research grant and contract funds.

Increasing numbers of investigators, particularly at the assistant and associate professor levels, receive all or a large part of their income from research grants and contracts. This situation arises not from reluctance to pay staffs from stable funds, or from misgivings as to the quality of the group whose salaries are derived from grants and contracts. The research programs of the nation have simply expanded more rapidly than the financial base of stable funds available to universities. This development has been necessary to expansion of research in universities, but it has had some unfortunate consequences. First, the number of investigators whose salaries are dependent upon renewable research grant or contract support has now become so large as to create an unhealthy degree of uncertainty as a built-in characteristic of the system. Second, many of the individuals concerned, and their families, lead a sort of hand-to-mouth—or grant-to-grant—existence. This is not conducive to the best work, nor is it an equitable arrangement. Third, the salary arrangements have tended in academic institutions to be a devisive force, by creating a group of scientists who have few—and in many cases no—teaching responsibilities. Finally, the system does not provide an adequate investment in the future research capacity of the nation by strengthening the teaching process to the optimum degree.

The Public Health Service, with the approval of the Congress, is in the process of initiating a program aimed directly at the solution of these problems in the fields of medical and related research. This article deals with the development of this program for increasing the stability of research careers in medical research through the grant program of the National Institutes of Health. In this presentation, in addition to defining the principles of the operation of this new program, we discuss some of the problems which have arisen during the early stages of its implementation. Most of these stem from new relations that are emerging between the federal research support programs and institutions of higher learning.

In essence, this is a case study of the problems which arise when the federal government supports research in universities which have responsibilities extending beyond research to teaching. If the federal government looks to the research capacity of the nation 10 or 20 years in the future, as well as its current research capacity, it must be concerned with the ability of the people who will be investigators in the coming

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