THE SPECTRUM OF LIGHTNING*

L. WALLACE
Kitt Peak National Observatory†
Received October 4, 1963; revised November 16, 1963

ABSTRACT

A re-examination of the lightning spectrum in the region 3150–9800 Å has revealed that some of the lines of O I and N I are Stark-broadened. In addition, unidentified absorption features have been observed in the interval 6100–6280 Å.

During the interval 1958–1962, a number of spectrograms of lightning were obtained incidental to investigations of the aurora and night airglow with the Meinel 9-inch *f*/0.8 spectrograph (Chamberlain 1955). These spectra, which are the result of reflections from clouds of many lightning strokes, are of somewhat greater resolution than those previously reported in the literature (Salanave 1961) and, as a result, show several new features. The purpose of this paper is to present the analysis of these spectrograms.

OBSERVATIONS

Halftones of the best spectra covering the region 3100–9600 Å are presented in Figures 1–7. The plates used for these illustrations are indicated in Table 1. The approximate dispersions in the first, second, and third orders are 66, 33, and 22 Å/mm, respectively. Plate No. 424 was taken without the aid of a filter so that both the second and third orders were recorded. The sections of the spectrum given in Figures 1, *b*, and 3, *b*, are those portions that are due to only a single order. The central portion of the plate, on which the two orders are overlapped, has been discarded. Plate No. 270 was taken when an aurora was in progress, but a comparison of this spectrogram with that of an aurora in the same region indicates that the densely overcast sky prevented all but the intense 5577 and 6300 Å auroral lines from being registered. Plate No. 352 was obtained using the customary ammonia hypersensitization technique. The response of this plate should be essentially flat from 8600 to 9800 Å. The analysis of plate No. 235 has been published elsewhere (Wallace 1960).

TABLE 1

Figure	Plate No.	Emulsion	Order
1*a*	253	103*a*O	III
1*b*	424	103*a*F	
2*a*	253	103*a*O	
2*b*, 3*a*	255	103*a*O	
3*b*	424	103*a*F	II
4*a*	267	103*a*F	
4*b*, 5*a*	270	103*a*F	
5*b*	276	103*a*F	
6	474	IN	I
7	352	IQ	

* *Contributions from the Kitt Peak National Observatory*, No. 52.

† Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

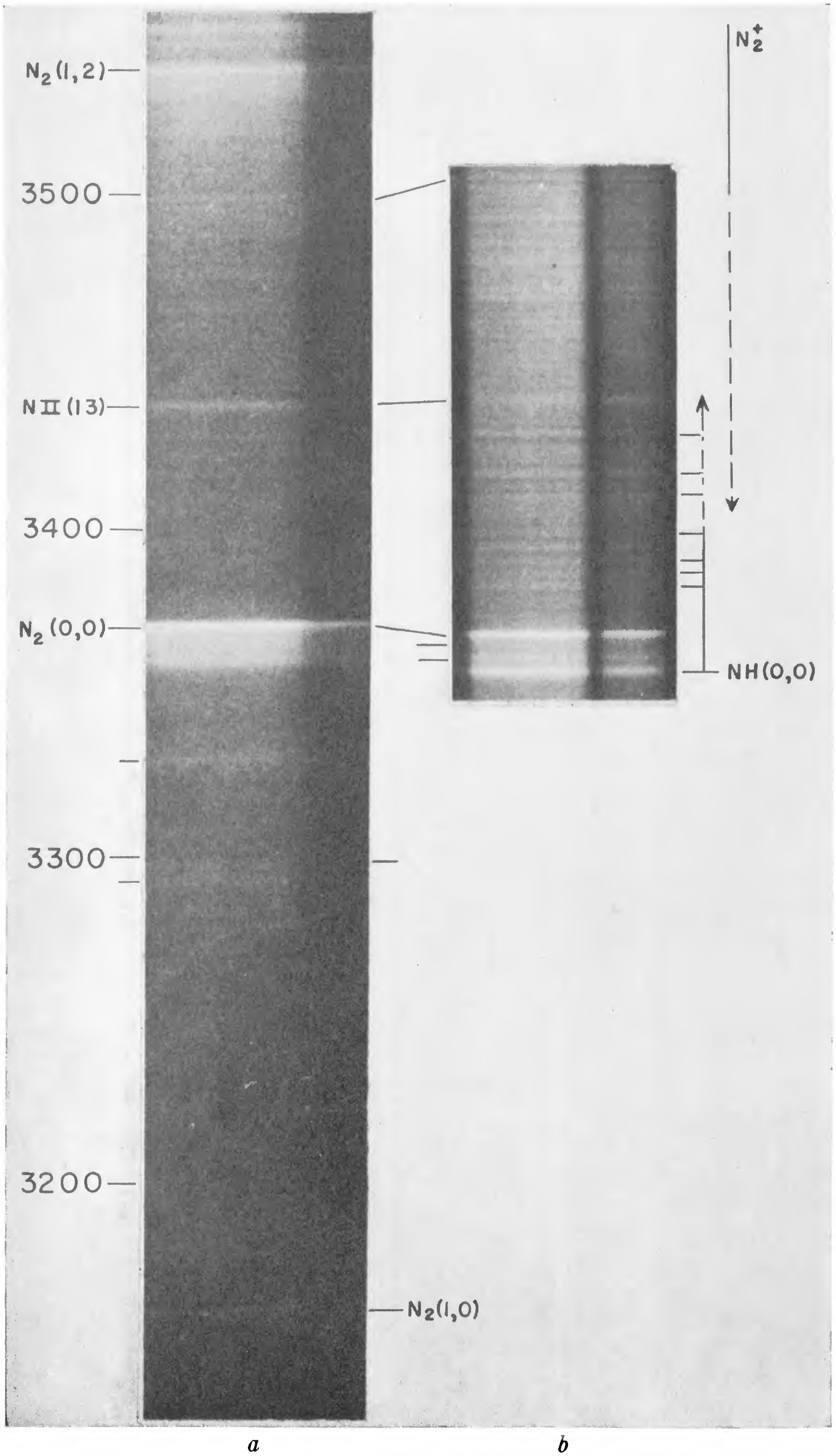
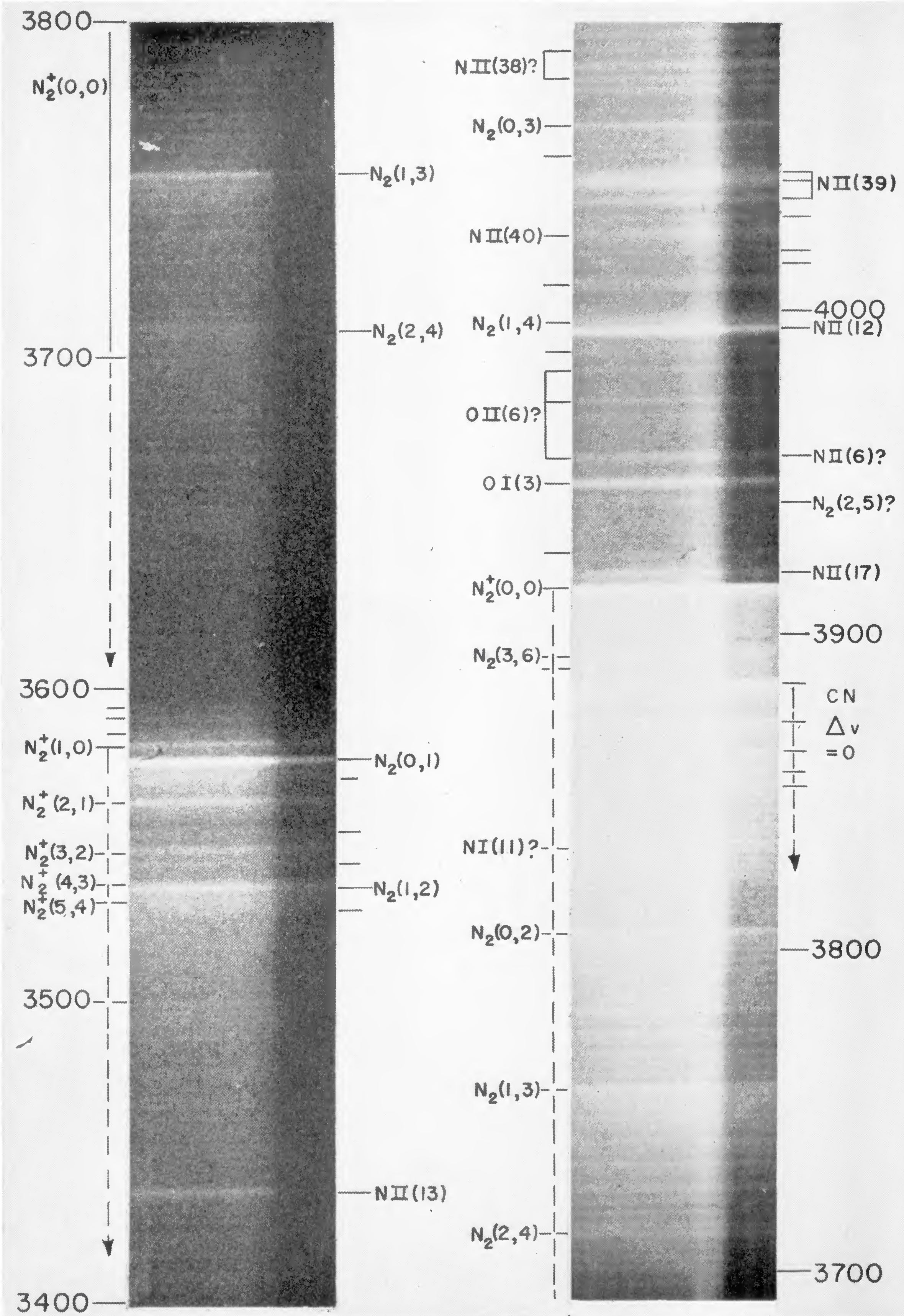
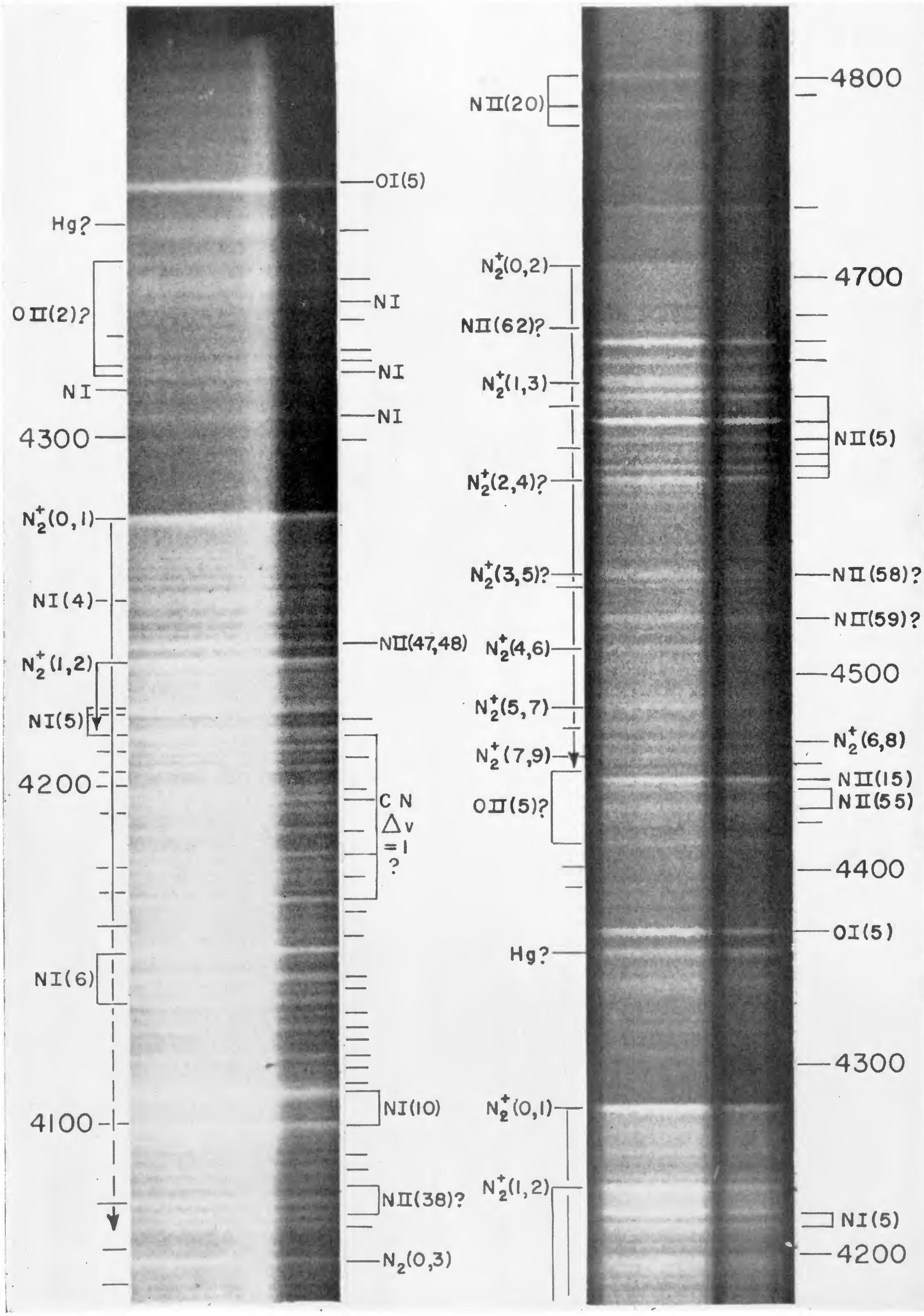


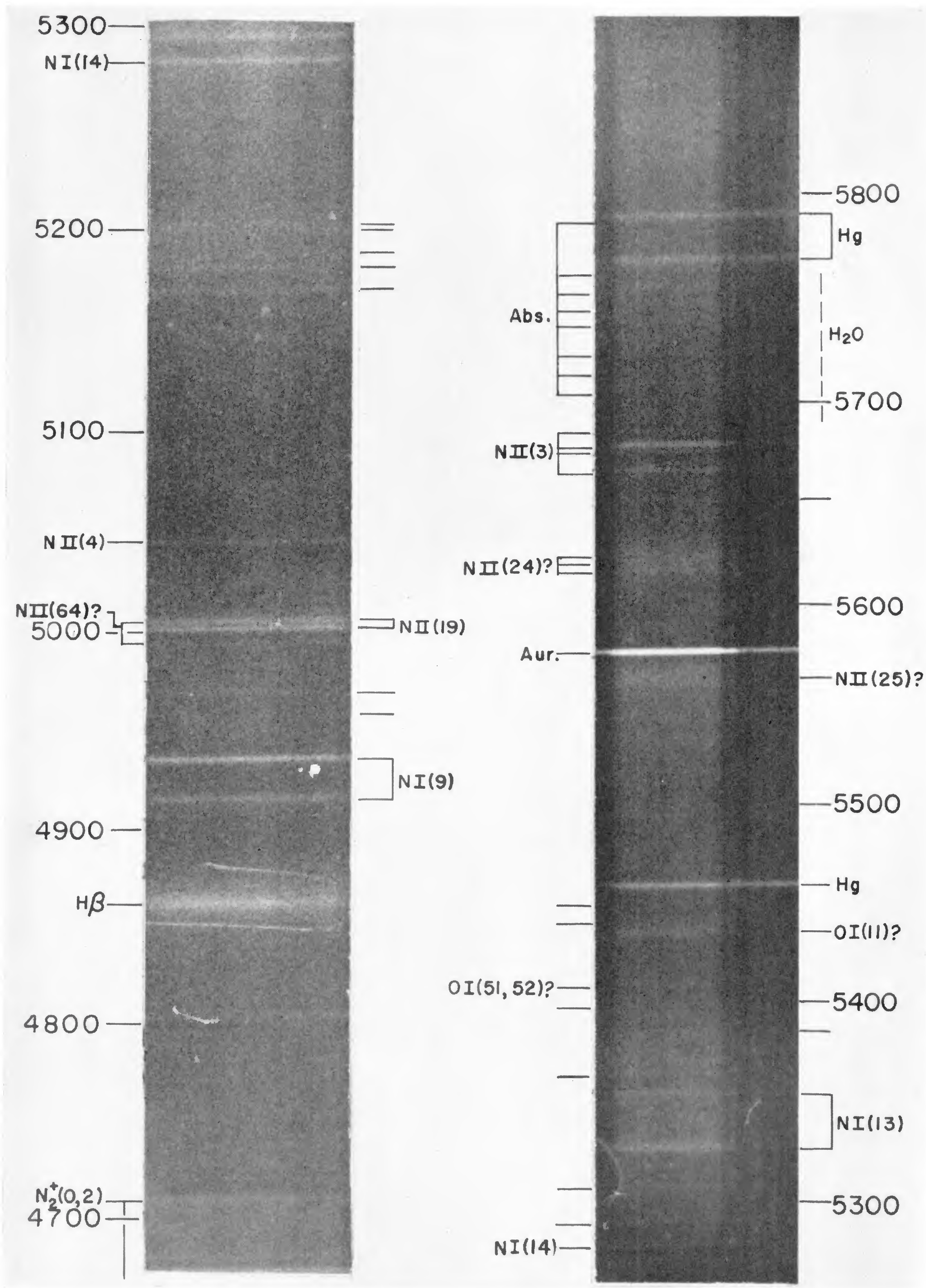
FIG. 1.—Lightning spectrum in the region 3150–3550 Å


3800
$N_2^+(0,0)$
$N_2(1,3)$
$N_2(2,4)$
3700
3600
$N_2^+(1,0)$
$N_2(0,1)$
$N_2^+(2,1)$
$N_2^+(3,2)$
$N_2^+(4,3)$
$N_2(1,2)$
$N_2^+(5,4)$
3500
N II (13)
3400
N II (38)?
$N_2(0,3)$
N II (39)
N II (40)
4000
$N_2(1,4)$
N II (12)
O II (6)?
N II (6)?
O I (3)
$N_2(2,5)$?
N II (17)
$N_2^+(0,0)$
3900
$N_2(3,6)$
CN
Δv
=0
N I (11)?
$N_2(0,2)$
3800
$N_2(1,3)$
$N_2(2,4)$
3700



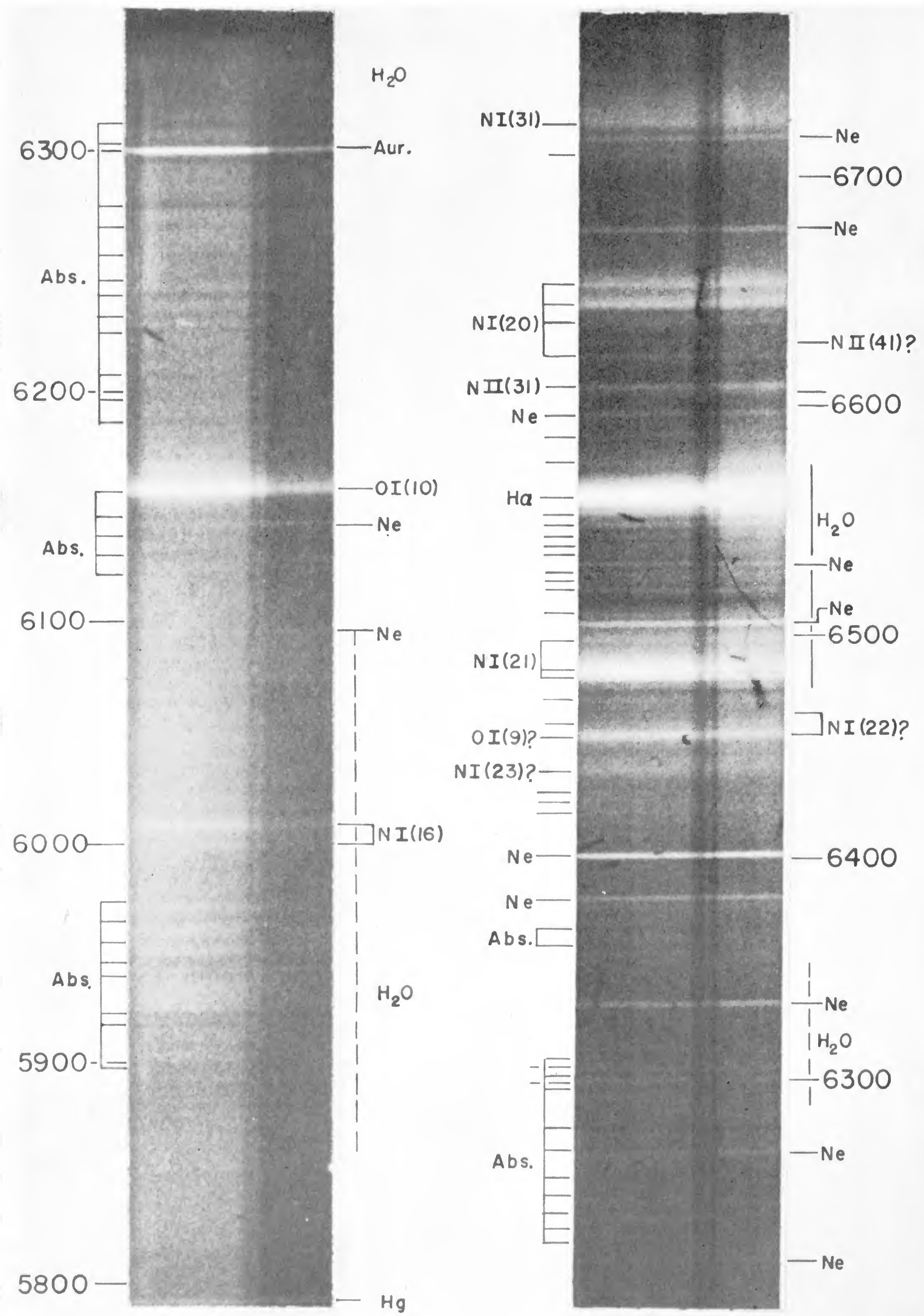
a *b*

FIG. 3.—Lightning spectrum in the region 4050–4830 Å



a *b*

FIG. 4.—Lightning spectrum in the region 4660–5880 Å



a *b*

FIG. 5.—Lightning spectrum in the region 5780–6770 Å

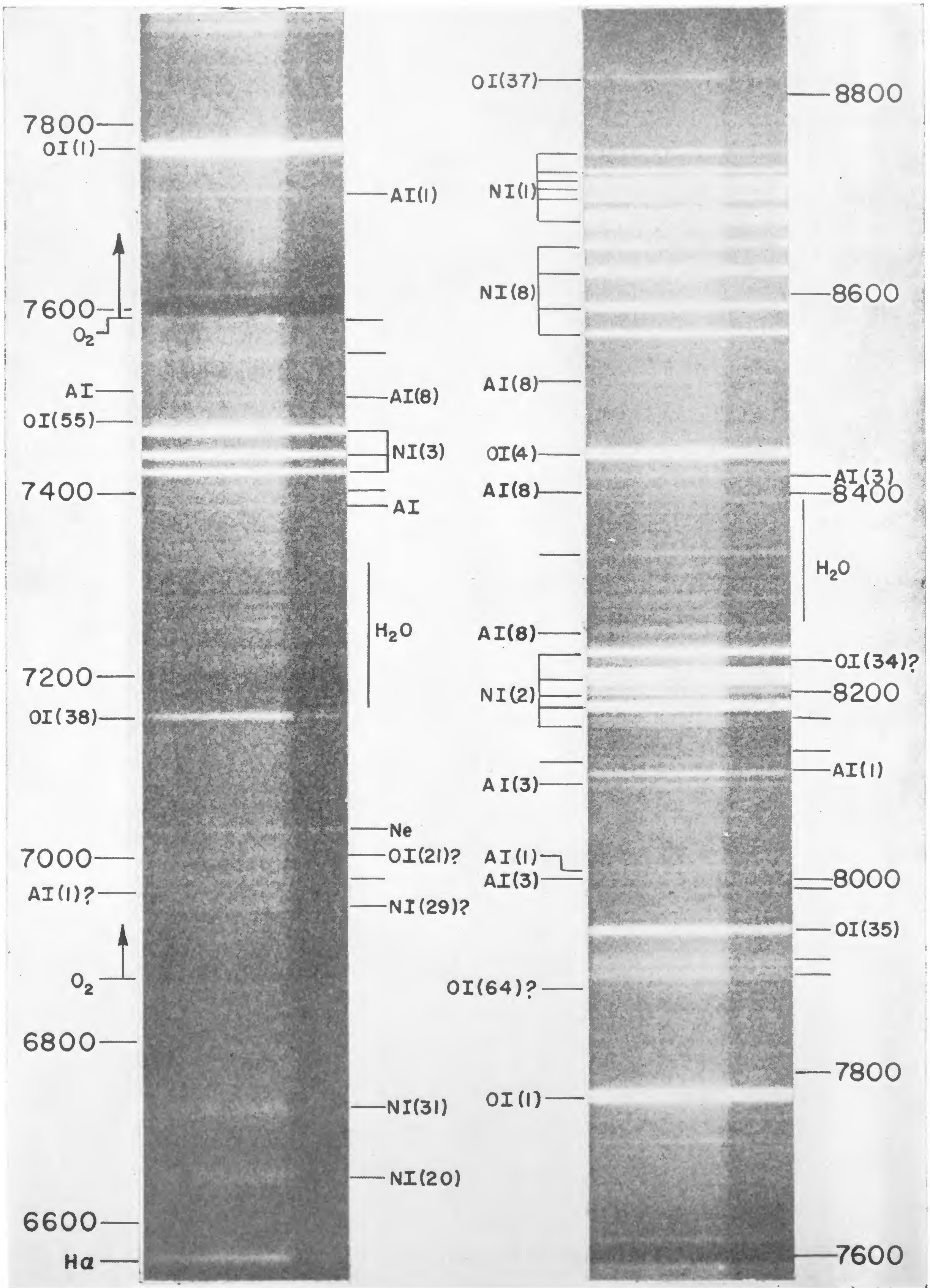


FIG. 6.—Lightning spectrum in the region 6550–8900 Å. The unidentified features at 7902.0 and 7914.4 Å are each doublets with about 4 Å separation.

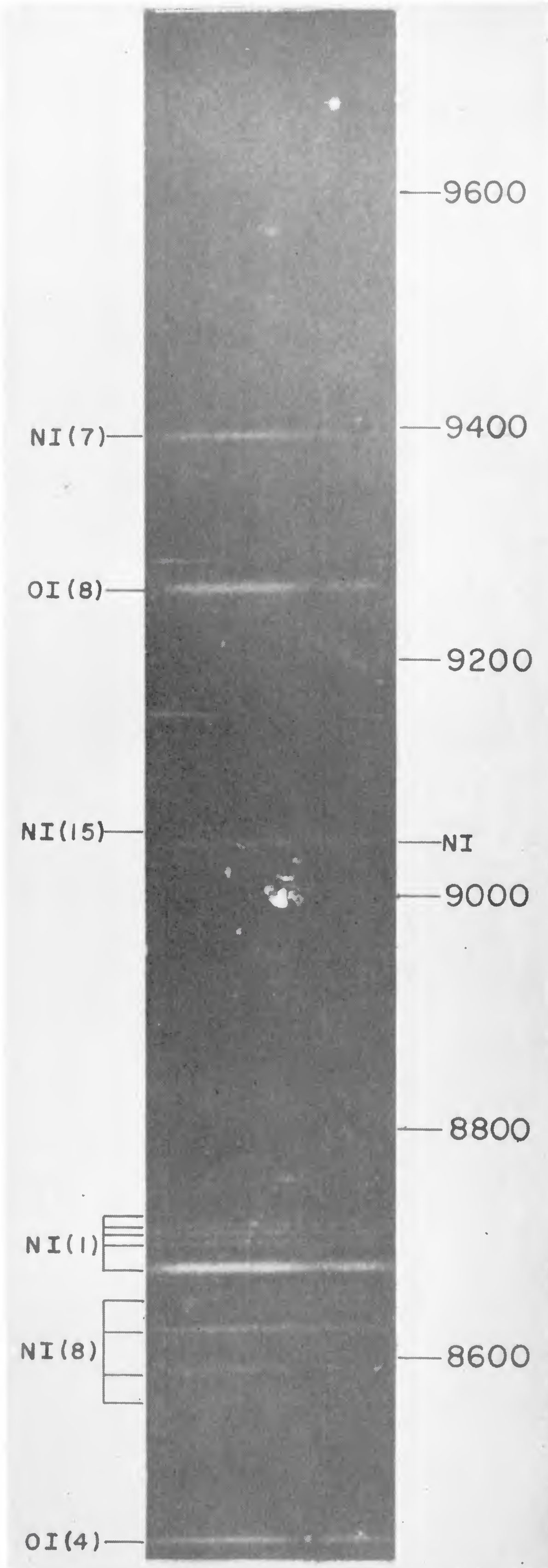


FIG. 7.—Lightning spectrum in the region 8430–9600 Å

RESULTS

A comparison of the measured wavelengths with the compilation of atomic line wavelengths given by Moore (1945) and the band-head tables of Pearse and Gaydon (1950) and Wallace (1962*a*, *b*) indicates that the majority of the previous identifications, made from lower-resolution material, is correct. A number of new multiplets of N I and O I have been identified, but these might have been expected on the basis of previously identified lines. Consequently, the list of measured wavelengths is not included here.

Moore's multiplet numbers, rather than the complete multiplet designations or the laboratory wavelengths, are given in the illustrations. The approximate extent of the band structure is indicated by rules extending from the heads. The extents which are uncertain, or expected but not completely verified (in the case of water vapor), are indicated by dashed rules. The leading lines which are not accompanied by atomic or molecular designations indicate unidentified features. The wavelengths of these features are too numerous to include here, but can be obtained from the author. The mercury and neon lines, because of their intensity variation in the direction normal to the dispersion, are clearly contaminants. The absorption features are listed in Table 3 (see below).

TABLE 2

λ_{meas}	NH(0, 0)	O_2(0, 14)
3985.1	84.8 P_7	85.0 P_{15}, R_{19}
88.6	88.5 P_8	88.4 P_{17}, R_{21}
91 9	92.1 P_9	92.2 P_{19}, R_{23}
95.8	95.7 P_{10}	96 5 P_{21}, R_{25}
3400 0	99.3 P_{11}	01.1 P_{23}, R_{27}
09.8	09 9 P_{14}?	11.4 P_{27}, R_{31}?
16.3	16.8 P_{16}?	17 2 P_{29}, R_{33}?
27.4	27.0 P_{19}?	....

Nitrogen bands.—The presence of the N_2 second positive and N_2^+ first negative bands is already well established. The present spectra add no new information regarding these systems.

CN violet bands.—The presence of the $\Delta v = 0$ sequence was established by Wallace (1960). The $\Delta v = -1$ sequence may also be present, but it is badly overlapped by other features. The $\Delta v = +1$ sequence might be identified with the features falling between the N_2^+ (1, 0) band and 3600 Å, but the observed spacing of these bands appears to deny the identification. Nonetheless, it seems quite likely that the CN bands do contribute to this spectral region.

NH.—Dufay (1949) suggested that the feature at 3360 Å was the *Q* head of the NH (0, 0) $^3\Pi$–$^3\Sigma$ band. The structure from 3772 to 3400 Å, as illustrated in Figure 1, *b*, has the same appearance as that of the *P* branch of this band when observed under laboratory conditions and comparable resolution (see Pearse and Gaydon 1950, Pl. 3; Gaydon 1957, Pl. 4*e*). The structure in the *R* branch is not discernable on the present spectra. In addition, the measurements of the features in this region, given in Table 2, are seen to be in good agreement with the laboratory measurements of the NH band (Funke 1935). The coincidences with P_{14}, P_{16}, and P_{19}, must, however, be fortuitous.

It is also apparent from Table 2 that the structure of the (0, 14) band of the Schumann-Runge system of O_2 (Lochte-Holtgreven and Dieke 1929) coincides with the observed structure. Since the head of this band is normally weak and would occur at 3370 Å, it might be present. However, the identification of the partially resolved rotational structure with NH appears preferable in view of the necessity of identifying the strong feature at 3360 Å and of the apparent lack of other structure that might be identified with the Schumann-Runge bands.

Dufay (1949) also observed features at 3253 and 3627 Å which he suggested might be identified with the (0, 0) and (0, 1) $^1\Pi$–$^1\Delta$ bands of NH. The first of these features falls in a region where our plates are poorly exposed and the second appears not to be present.

N I.—It is clear from Figure 5, *b*, that the lines of multiplets 21, 20, and 31 are considerably broader than the instrumental profile. They have a sharp short-wavelength edge and are shaded to long wavelengths. All of these lines fall in a single spectrogram and no other diffuse lines, except possibly those of multiplet 16 at 6000 Å are observed. Additional spectrograms, not so well exposed, also show the diffuse character of these features and indicate the variability of the widths of these lines.[1] It is also clear from Figure 6 that not all lines of N I are diffuse.

An examination of the energy-level diagram shows that since the lines of multiplets 1 and 2 are sharp, only the upper levels of multiplets 21, 20, and 31 are broadened. Multiplet 22, which might possibly be broadened, could only indicate that the upper level is diffuse. Multiplets 24 and 25 have only been tentatively identified and should, therefore, probably not be drawn into the present discussion.

One can generalize the situation regarding the quartet-quartet transitions by saying that the most certain of the observations indicate that the levels between 13.55 and 13.65 eV are diffuse, the lower levels are sharp, and no lines originating from higher excitation potentials are positively identified. This result points clearly to Stark-broadening.

Of the doublet-doublet transitions, the only positively identified multiplet that may be diffuse is No. 16. If we assume that it is the upper level of this multiplet that is diffuse, and not the lower, the observed sharp appearance of multiplet 10 would seem to indicate that one can only safely say that the levels within 1 eV of their corresponding ionization potential are either diffuse or no transitions from these levels are clearly identified. The levels at less than 1.25 eV below the ionization potential are sharp.

N II.—No surprising multiplets have been identified and none of those observed is diffuse. The highest observed level is 3.4 eV below the ionization potential.

O I.—Of the positively identified transitions, only multiplet 10 is observed to be diffuse, and again, it is clear that it is the upper level, falling 0.85 eV below the ionization potential, that is diffuse. No lines with upper levels closer to the ionization potential could be positively identified.

O II.—In accord with most of the previous investigations, no lines of O II could be positively identified.

H.—Only Hα and Hβ could be positively identified. The diffuse appearance of these features, previously noted by Dufay and Dufay (1949) and interpreted as due to Stark-broadening, is confirmed.

A I.—The present observation of argon lines in the near-infrared is in excellent accord with the results of Petrie and Small (1951). In Geisler discharges through argon, the infrared lines are by far the brightest of all those observed in the photographic region. Consequently, since the infrared argon lines are not very prominent in the lightning spectrum, it would not be surprising if they were difficult to identify in the visible. Indeed, even though the wavelength calibration spectrum is a discharge through a neon-argon mixture, none of the fainter lines at wavelengths less than 6950 Å were observed. This result is, however, not necessarily in disaccord with Salanave, Orville, and Richards' (1962) identifications of neutral and singly ionized argon lines in the region from 4000 to 6000 Å, since these authors have noted other significant differences, particularly with regard to the intensities of the CN and N_2^+ bands.

[1] Knuckles and Swensson (1952) have also remarked that multiplet 21 was shaded to longer wavelengths. Multiplets 20 and 31 were reported as diffuse.

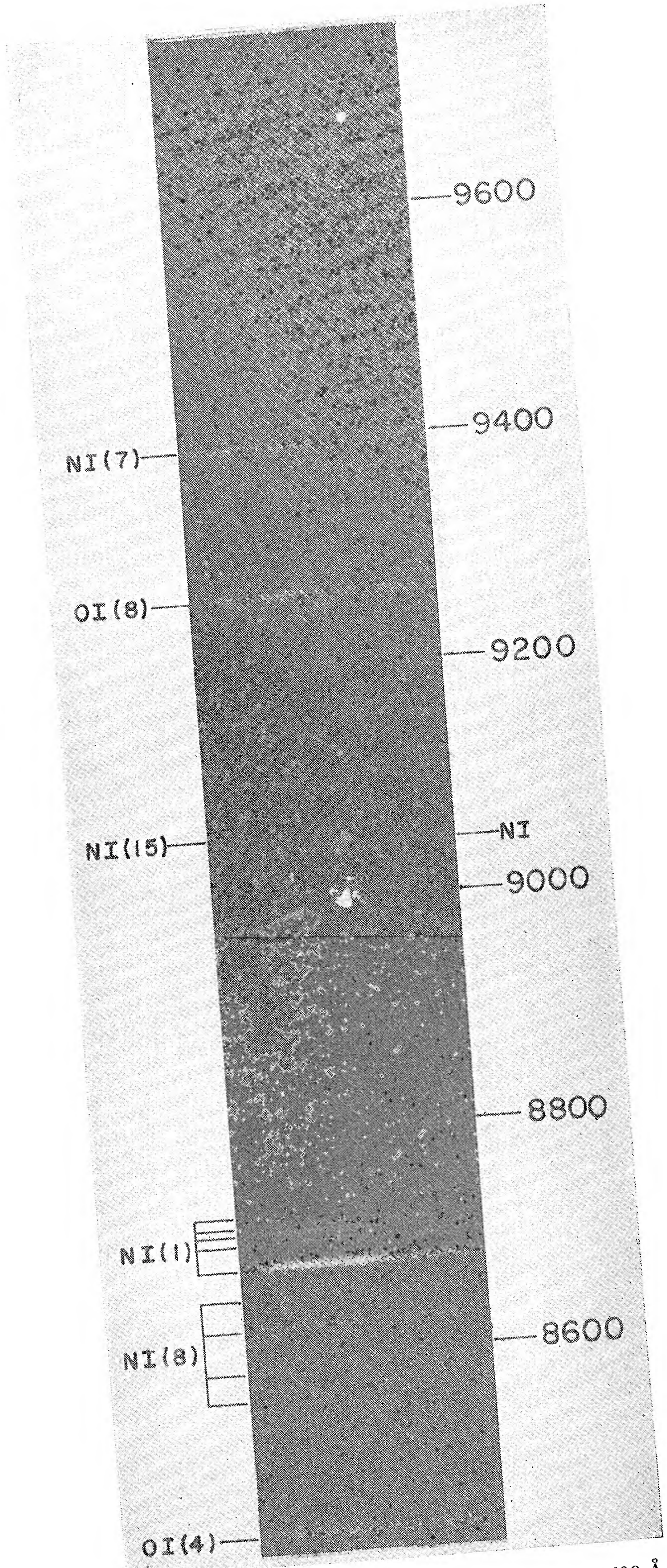


FIG. 7.—Lightning spectrum in the region 8430–9600 Å

C I.—Petrie and Small (1951) identified lines at 9061 and 9078 Å with neutral carbon. The line at 9078 Å does not appear on the present spectra and that at 9061 Å is readily identifiable with N I.

Continuum.—A continuum extends from at least 4700 Å to longer wavelengths. Below 6800 Å this continuum is due to lightning, but from about this wavelength to 8800 Å the continuum is no stronger than that due to street lighting when there is no aurora. Consequently, no information can be obtained on the lightning continuum above about 7000 Å, nor can any information on the energy distribution of this continuum be obtained from the present observations. Below 4700 Å there are not enough gaps in the emission spectrum to permit the positive identification of the continuum.

Absorption features.—It is possible to compare the first-order spectra in the region 6600–8800 Å (Fig. 6) with spectra obtained with the same equipment on cloudy nights in the absence of lightning storms. In this way, it is easy to establish that the absorptions observed in the lightning spectra in this region are just the usual "telluric" water vapor and O_2 features. This is, of course, to be expected since it appears that lightning makes no appreciable contribution to the continuum in this region.

TABLE 3

ABSORPTION FEATURES

λ(Å)	λ(Å)	λ(Å)
5702 8	46 9	32 7
12 0	56 5	40 5
20 7	67 4	48 1
35 8	76 3	57 6
44 1	6120 7	69 8
52 6	29 9	77.6
60 3	37 9	96 7
84 7	46 5	6303 9
5898 3	6189 2	11 3
5918 3	98 2	6360 6
22 8	6206 3	68 7
40 7	25 1	

Below 6600 Å, where no "telluric" spectra at comparable resolution are available, I have compared the lightning spectra with the high-resolution laboratory observations of the water-vapor spectrum (Baumann and Mecke 1933; Freudenberg and Mecke 1933) and the "telluric" spectrum (St. John, Moore, Ware, Adams, and Babcock 1928). From this comparison, it appears that the 6524 Å water-vapor band adequately accounts for the absorptions in the neighborhood of Hα. At shorter wavelengths, the line-by-line identifications are not as convincing, but the over-all agreement points to water vapor as the absorber, except in the region 6100–6280 Å where the laboratory and telluric water-vapor spectra show no absorptions. The wavelengths of the more prominent absorption features in the range 5700–6400 Å are given in Table 3.

I am indebted to Dr. Luise Herzberg and Dr. J. Rand McNally, Jr., for their comments on various aspects of this paper.

This work was initiated while the author was at Yerkes Observatory of the University of Chicago and was there supported in part by the Geophysics Research Directorate of the Air Force Cambridge Research Laboratories, Air Force Research Division under Contract AF19(604)-3044, and in part by the National Aeronautics and Space Administration through Research Grant NSG 118-61.

REFERENCES

Baumann, W., and Mecke, R. 1933, *Zs. f. Phys.*, **81**, 445.
Chamberlain, J. W. 1955, *Ap. J.*, **121**, 277.
Dufay, J., and Dufay, M. 1949, *C.R.*, **229**, 838.
Dufay, M. 1949, *Ann. geophys.*, **5**, 255.
Freudenberg, K., and Mecke, R. 1933, *Zs. f. Phys.*, **81**, 465.
Funke, G. W. 1935, *Zs. f. Phys.*, **96**, 787.
Gaydon, A. G. 1957, *The Spectroscopy of Flames* (New York: John Wiley & Sons).
Knuckles, C. F., and Swensson, J. W. 1952, *Ann. geophys.*, **8**, 333.
Lochte-Holtgreven, W., and Dieke, G. H. 1929, *Ann. Phys. Leipzig*, Ser. 5, **3**, 937.
Moore, C. E. 1945, Contrib. Princeton Obs., No. 20.
Pearse, R. W. B., and Gaydon, A. G. 1950, *The Identification of Molecular Spectra* (2d ed.; London: Chapman & Hall).
Petrie, W., and Small, R. 1951, *Phys. Rev.*, **84**, 1263.
St. John, C. E., Moore, C. E., Ware, L. M., Adams, E. F., and Babcock, H. D. 1928, Publication No. 396, Carnegie Institution of Washington.
Salanave, L. E. 1961, *Science*, **134**, 1395.
Salanave, L. E., Orville, R. E., and Richards, C. N. 1962, *J. Geophys. Res.*, **67**, 1877.
Wallace, L. 1960, *J. Geophys. Res.*, **65**, 1211.
———. 1962*a*, *Ap. J. Suppl.*, Vol. **6**, No. 62.
———. 1962*b*, *ibid.*, Vol. **7**, No. 68.