SPECTROPHOTOMETRIC STUDIES OF GASEOUS NEBULAE

I. THE DOUBLE-RING PLANETARY NGC 7009

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ABSTRACT

Spectrophotometric data obtained with a photoelectric spectrum scanner at Mount Wilson Observatory in 1956 and Mount Stromlo Observatory in 1961 are combined with photographic observations obtained with coudé spectrographs at Mount Wilson and Lick Observatories to obtain line intensities and identifications in the spectral region λ 3100–λ 4960. Lines as weak as 0.02 on the scale I (Hβ) = 100 are measured on the longest exposure.

I. INTRODUCTION

This is the first of a series of papers devoted to the measurement of line intensities in gaseous nebulae—particularly planetary nebulae. The purpose of the investigation is to supply intensities for weak as well as strong emission lines, which are of interest in connection with theoretical studies of the physics and chemical composition of gaseous nebulae.

Accordingly, we confine our attention to measurements of the nebular lines, deferring theoretical treatments to separate papers which are in preparation. Advances in telescopes and spectrographs in the last quarter-century enable us to supplement and extend the classical investigations of Bowen and Wyse and to increase the accuracy of measurement by a judicious combination of photographic and photoelectric techniques.

The photographic observations have been obtained with the coudé spectrographs at the Lick and Mount Wilson Observatories. They are calibrated with the aid of photoelectric observations, most of which have been published by various observers.

Because we must cover a wavelength range that can extend from λ 3000 to λ 11000 and compare lines that can differ in intensity by a factor of 25000, nebular spectrophotometry presents some unique difficulties. As in ordinary photometry we profit by a judicious combination of photographic and photoelectric techniques.

Photoelectric photometry possesses the advantage of a linear relation between intensity and signal and a high intrinsic accuracy. It suffers from the disadvantages that one may observe only one line at a time and only moderately strong lines at that, and from poor spectral resolution. The photographic plate, although capable of high spectral resolution and the simultaneous registration of much of the spectrum, suffers from the disadvantages of non-linear response characteristics, a limited intensity range on any one exposure, and reciprocity failure.

Thus, by photoelectric photometry, we may first compare the nebula with a standard star to establish the intensities of the brighter lines (Liller and Aller 1954, 1963; O'Dell 1963) and then use these line intensities as known standards in our reduction of the photographic measurements. The relation between blackening of the plate or microphotometer deflection and intensity follows from laboratory calibration, but the influence of the wavelength-dependence of the sensitivity of the plate, of the transmission of the optics, and atmospheric extinction can be obtained by comparing the raw photographic intensities with the final photoelectric intensities.

Several plates of different exposure times are required to cover the range of intensities from the weakest lines observed photoelectrically to the weakest lines observed photographically. A single plate may cover a substantial spectral range and give precise data on lines within a certain intensity range. If the exposure times are correctly chosen, the stronger measurable lines of the plate of shortest exposure will correspond to the weaker lines measured photoelectrically. Hence a comparison of the "true," i.e., photoelectric, intensities with those derived from the photographic plate enables us to extract the "plate-sensitivity plus instrumental-transmission plus atmospheric extinction curve" and to calculate relative intensities of all lines on the plate. We then proceed to the successively longer exposures, each of which contains lines that are measurable both on it and on the shorter and longer exposures. Thus the photoelectric measurements enable us to construct the intensities of the faintest lines in the spectrum.

In studies of objects such as NGC 7009 it is possible to use the central star (whose spectrum is photographed on some of our plates) as a check on the plate-sensitivity–instrument–atmosphere-extinction-curve. We consider the star to radiate as a black body at its Zanstra temperature.

One loses accuracy in each step of the procedure. Furthermore, care must be taken to allow for the lower purity of the photoelectric spectral scans, particularly in crowded regions of the spectrum.

II. SOME CHARACTERISTICS OF NGC 7009

The planetary nebula NGC 7009 is one of the best-known examples of these objects. Sometimes called the "Saturn" nebula because of its two distinctive ansae, it has been the subject of many investigations. Berman (1930) made the first photometric measurements and isophotic contours. Spectrophotometric measurements extending to the ultraviolet were made in 1938–1939 (Aller 1941). Bowen and Wyse (1939) and Wyse (1942) made a very detailed study of the spectrum and estimated the chemical composition of the nebula, as did also Aller and Menzel (1945) and Aller (1961). Photoelectric measurements of the surface brightness with a photometer equipped with interference filters (Liller 1955) were supplemented by measurements of the relative intensities of N_1, N_2, and Hβ by Liller and Aller (1954), who used an objective prism on the Curtis-Schmidt telescope. With a spectrum scanner attached to the 60- and 100-inch reflectors at Mount Wilson in 1956, Liller and Aller (1963) measured the relative intensities of the principal lines.

O. C. Wilson (1950, 1958) measured the internal motions in NGC 7009, showing the shell to have a non-spherically symmetrical expansion. These data, in conjunction with isophotic contours of the stronger lines measured on Mount Wilson 100-inch coudé plates secured by Wilson with the aid of an image rotator, and on 200-inch direct photographs secured by Minkowski, permit one to assess the spatial distributions of the radiating material.

The nebula shows a rather "soft" structure and the density obtained from the λ 3726/λ 3729 ratio does not depart too far from that estimated from the surface brightness. Although sizable density fluctuations exist, extremely compact condensations such as those observed in NGC 2392 appear to be lacking.

Wyse (1942) emphasized the large number of recombination lines of O II, C II, etc., many of which are not observed even in NGC 7027. Accordingly, an intensive study of the spectrum of this object seemed justified in an effort to obtain intensities for both weak and strong lines. One object of this particular investigation was to obtain the intensities of recombination lines for comparison with intensive theoretical investigations which are being carried out on this problem.

Our measurements are confined to the brighter ring, although the stronger lines have been measured in the ansae which have much lower excitation (Aller 1941). As in NGC 7027 the background continuum (due to H recombination, 2-photon emission, etc.) imposes a limitation on the intensities of the weakest lines that can be observed. Not much could be gained by going to higher dispersion as resolution becomes limited by Doppler breadth of the lines. Figure 1 reproduces a portion of the spectrum.

We have identified recombination lines of the following ions: H I, He I, He II, C II, C III, O II, O III, O IV, Ne II, Mg I, Mg II, Si II, Si III, Si IV, S II, S III, and Ar II. The Mg I λ 4571 and Si II λ 3856, λ 3861 lines are probably excited by electron collisions. The O III and N III lines of the Bowen fluorescent mechanism are well represented. The forbidden lines include [O II], [O III], [Ne III], [Ne V], [S II], [S III], [Ar IV], [K V], [Fe II], [Fe V] and possibly [F IV].

Table 1 lists the coudé plates used in the present investigation. Successive columns give the plate number, the telescope (Lick 120-inch and Mount Wilson 100-inch), the exposure time, and the date of the observation.

TABLE 1

OBSERVATIONS OF NGC 7009

Plate No.	Telescope	Exposure Time	Date
Ec 1507	120-inch	120 min	Oct. 18, 1962
Ce 14763	100-inch	300 min	Aug. 29, 1961
Ce 14765	100-inch	459 min	Aug. 30, 1961
Ce 14767	100-inch	906 min	Aug. 30–Sept. 1, 1961

TABLE 2

ADOPTED PHOTOELECTRIC INTENSITIES

λ	*I* (Aller and Faulkner)	*I* (Liller and Aller)	λ	*I* (Aller and Faulkner)	*I* (Liller and Aller)
3133	8 40	...	4026	3 15	3 1
3187	2 14	...	4068+76	...	2 5
3203	3.22	...	4101	24 8	28 3
3312	1 83	...	4340		49 1
3341	3 05	...	4363		8 4
3444	7 29	6 1	4388	...	2 7
3712	2 71	...	4471	...	6 0
3727	20 0	18 5	4640+58	...	6 3
3750	3 83	3 9	4686		16 8
3770	2 78	3 8	4712		5 7
3797	3 76	5 2	4740	...	4 7
3835	6 10	8 8	4861	...	100
3868	102 0	99 3	4959		351
3889	19 3	18 4	5007		1027
3970	46 5	48 4			

The photoelectric intensity measurements listed in Table 2 are taken from measurements by Liller and Aller (1963) and from Aller and Faulkner (unpublished), who used Liller's photoelectric scanner at the 74-inch reflector on Mount Stromlo.

We first calibrated the Lick photographic intensities against the photoelectric measurements. The Mount Wilson data, which were first reduced to a common scale and averaged, were compared with both the corrected Lick intensities and the photoelectric results to provide the final calibration curve for the weak lines.

Table 3 lists the final results. Successive columns give the measured wavelength, the identification of the line, the multiplet number in Miss Moore's *Revised Multiplet Table* (RMT), and the finally adopted intensity on the Bowen-Wyse scale, $I(H\beta) = 100$. In the case of blends, the most important contributor, when known, is italicized.

Errors in the calibration curves can give a wavelength-dependent error so that in-

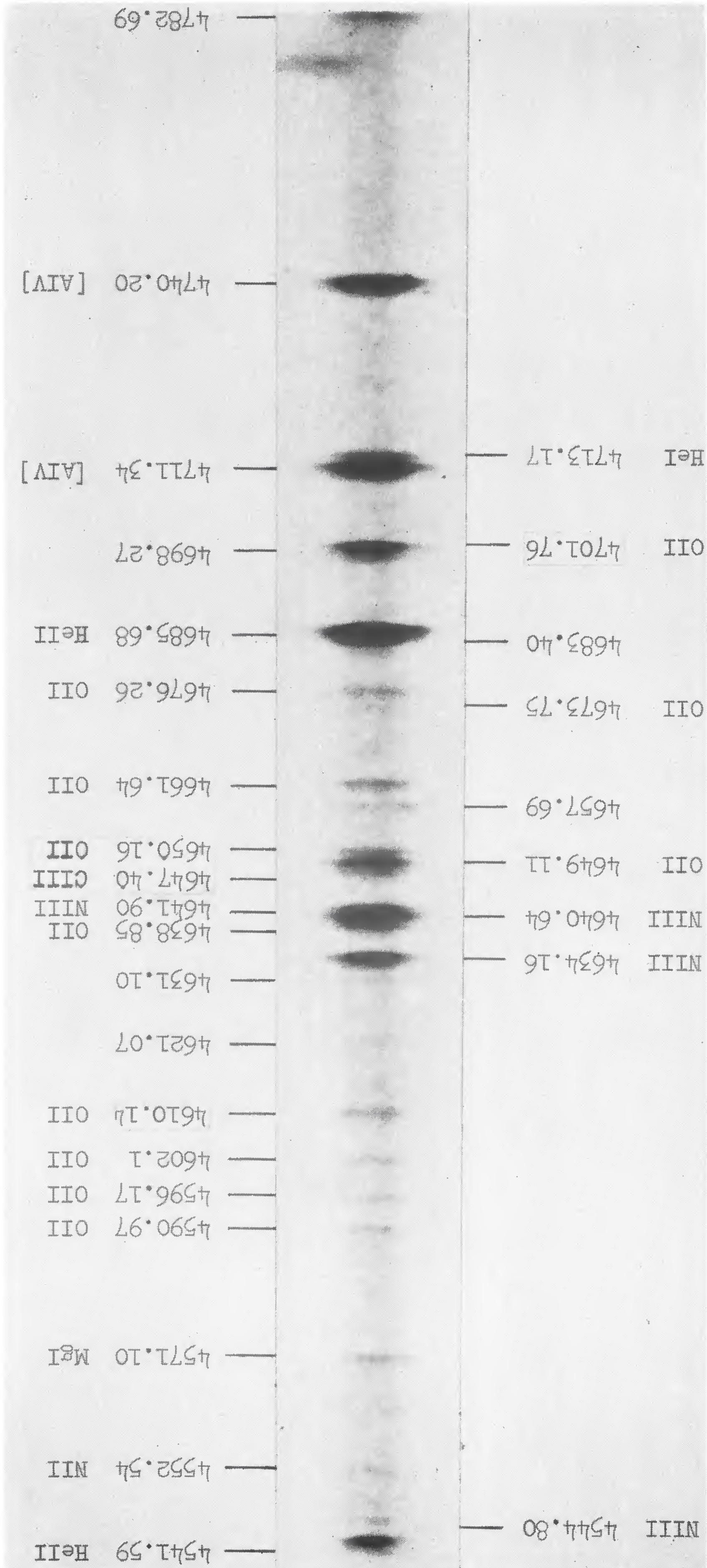

FIG. 1.—Spectrum of NGC 7009

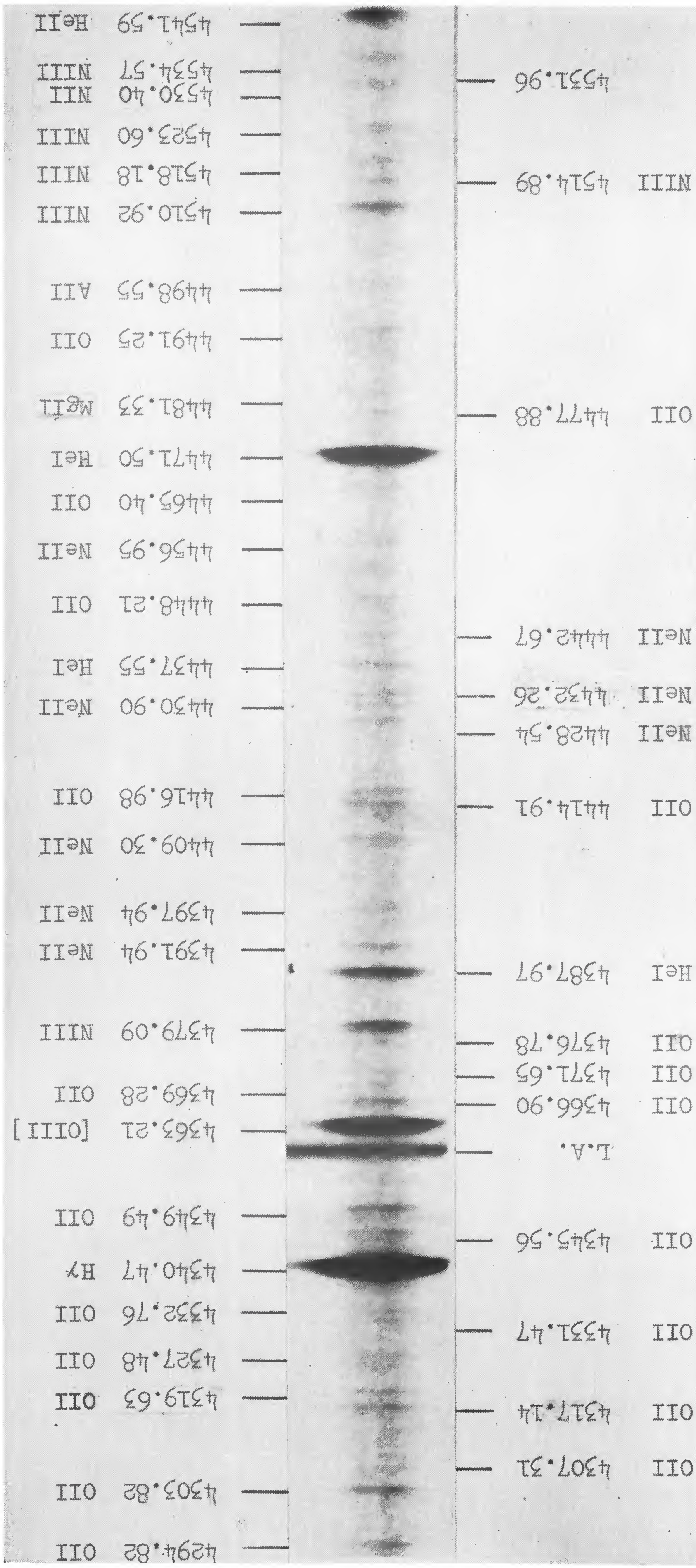

FIG. 1.—*Continued*

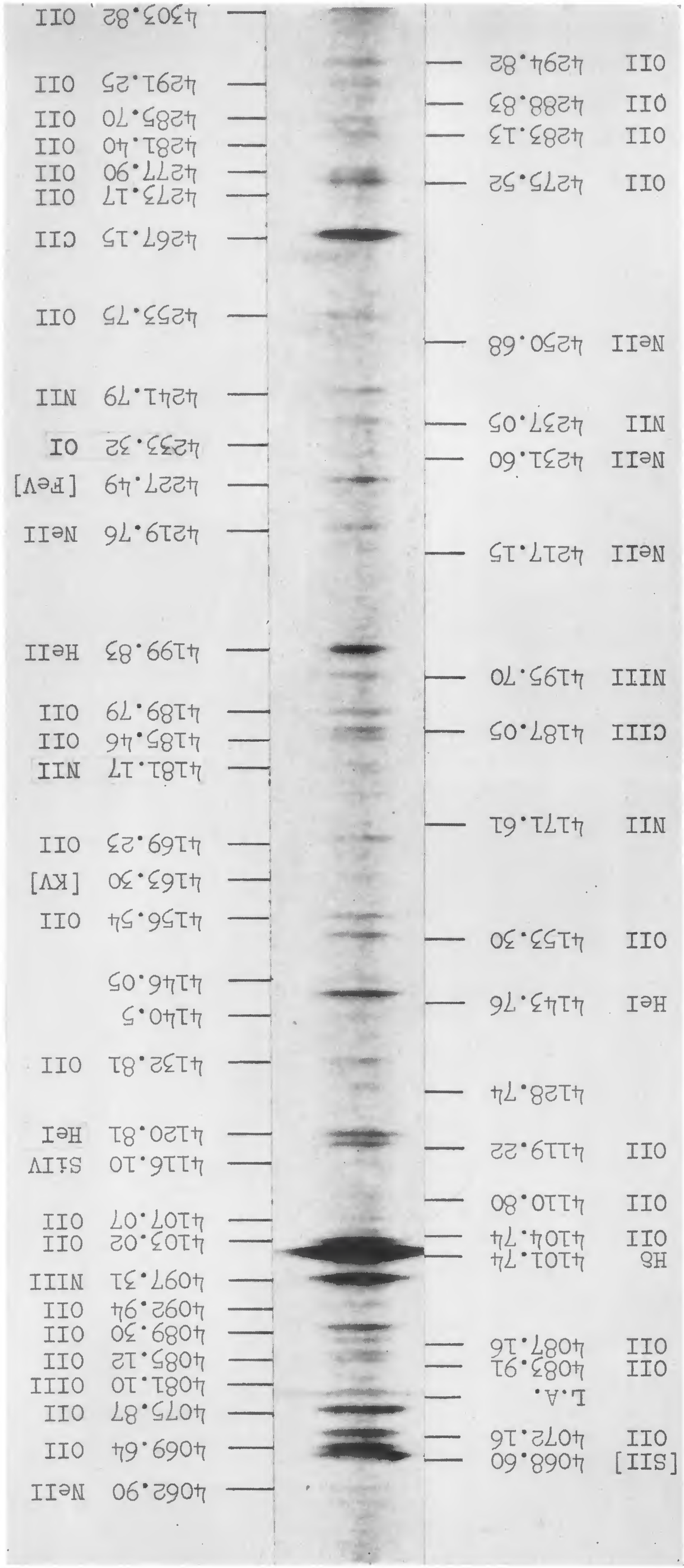

FIG. 1.—*Continued*

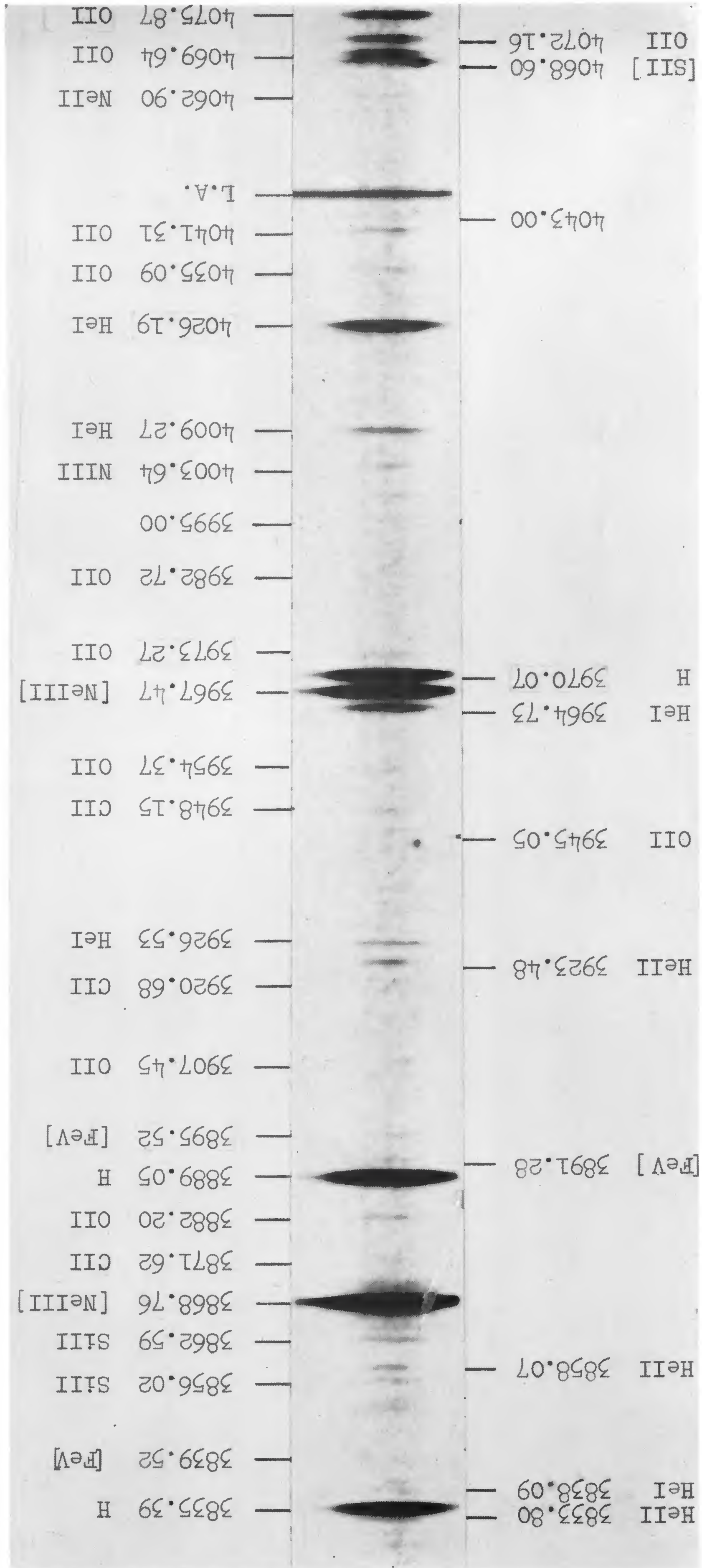

Fig. 1.—*Continued*

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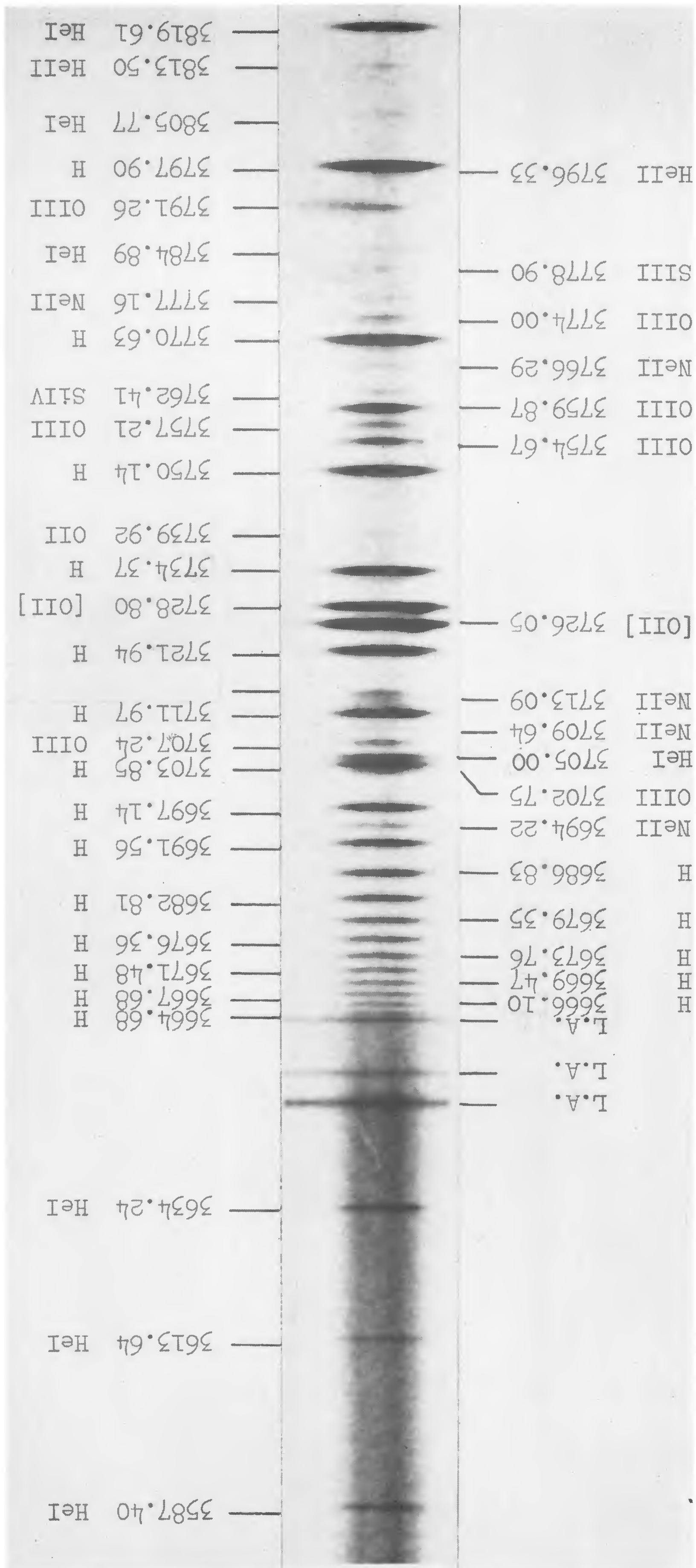

FIG. 1.—*Continued*

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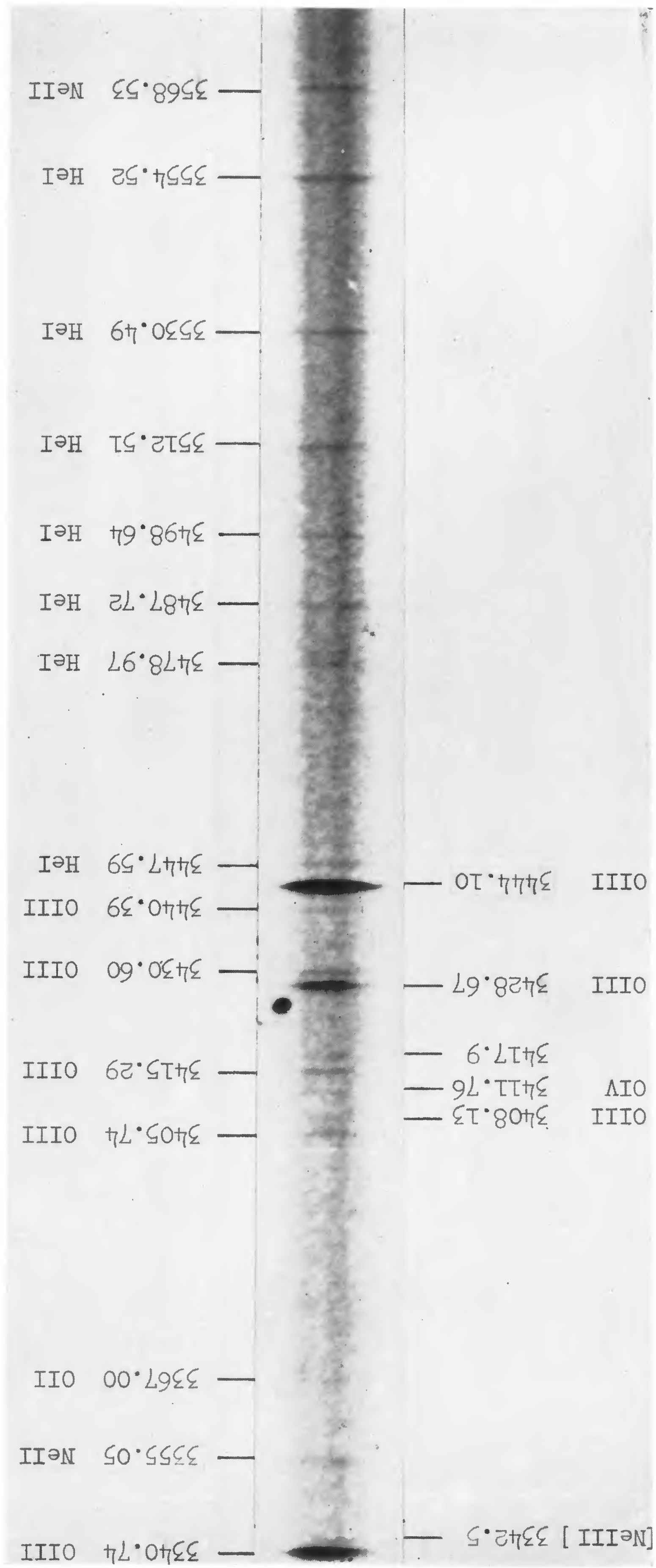

FIG. 1.—*Continued*

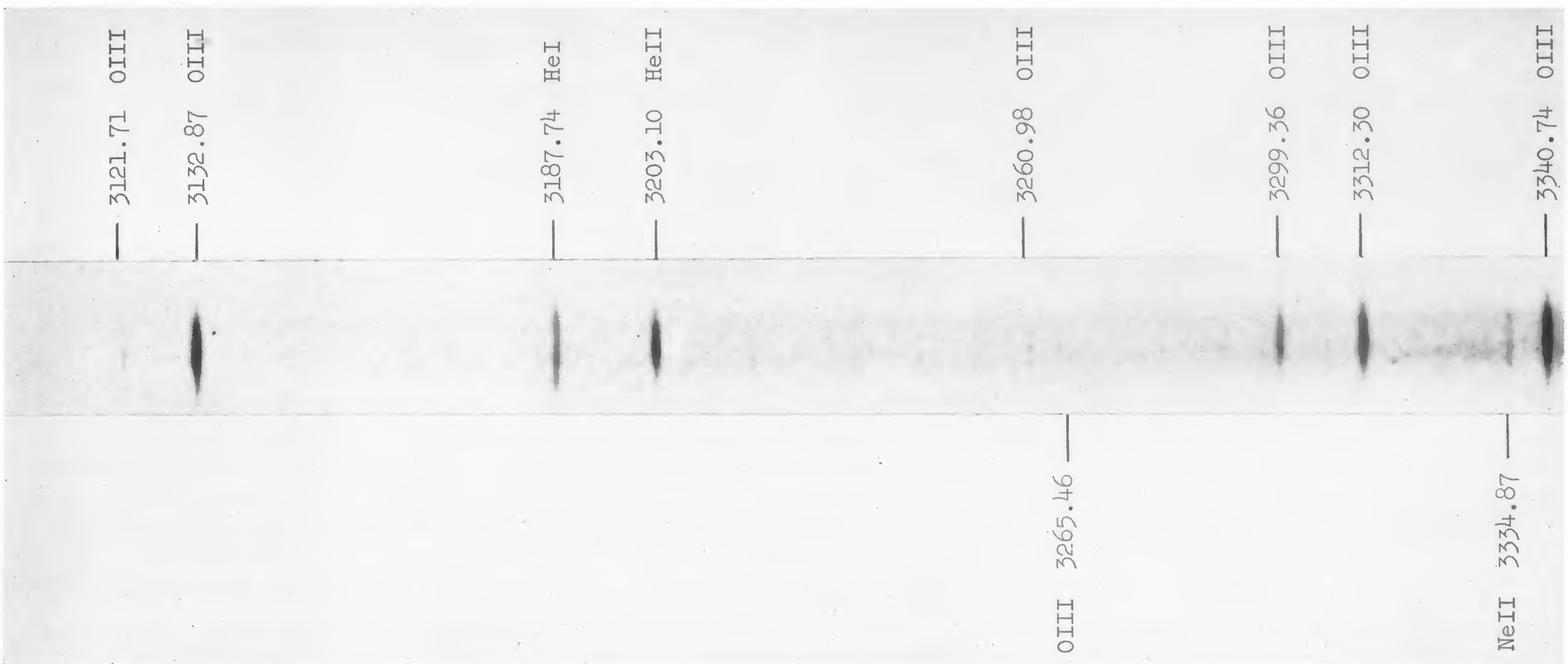

FIG. 1.—*Continued*

TABLE 3

SPECTRUM OF NGC 7009

λ	Ident	Mult	I
3121 71	O III	12	0 84
3132 87	O III	12	9 5
3187 74	He I	3	1 5
3203 10	He II	1	3 0
3260 98	O III	8	0 16
3263 43	Ne II	15	0 15
3265 46	O III	8	0.11
3267 3	O III	8	0 06
3299 36	O III	3	0 91
3305 15	O II	23	0 05
3306 60	O II	23	0 88
3312 30	O III	3	2 12
3334 87	Ne II	2	0 28
3340 74	O III	3	2 82
3342 5	[Ne III]	2*F*	0 18
3354 92	{He I Ne II}	8 2	0 18
3367 00 .	O II	52	0 10
3375 74	O II	52	.
3392 78	Ne II	7	. . .
3397 90	Ne II	36	0 04
3399 80	[Fe V] ??	4*F*	0 05
3405 74	O III	15	0 14
3408 13	O III	15	0.08
3411 84	{Ne II O IV}	45 2	0 05
3414 8 . .	{Ne II O III}	20 15	0.18
3417 7	Ne II	20	0 07
3425 57	{Ne V O IV}	1 3	*
3428 70	O III	15	1.20
3430 55 .	O III	15	0 21
3438 35 .	{Ar II ?? Ne II ??}	58 45	0 07
3440 32	O III	13	0.08
3442 00	Ne II	36	0 06
3444 00	O III	15	5 25
3447 59	He I	7	0 13
3450 78	O III	25	. . .
3464 21	Ar II ??	70	0 05
3466 04	He I		0 02
3468 44	K III	1	0 04
3472 00	He I	44	0 03
3478 95	He I	43	0 06
3480 80	Ne II	49	. . . .
3487 77	He I	42	0 02
3494 55	O II	70	0 04
3498 70.	He I	40	0 07
3504 23	. .	. .	0 05
3512 51	He I	38	0 06
3520 40	Ne I ??	7	
3525 38	. .	.	. .
3530 58	He I	36	0 14
3554 55	He I	34	0 17
3563 11	O IV	12	. . .
3568 62 . .	Ne II	9	0 12
3570 27	. .	. .	. . .
3574 29	Ne II	9	0 03
3578 08	.	.	0 02
3580 05			. . .
3583 03	. . .	. .	0 03
3587 36 .	He I	31	0 23
3597 91	. .		. . .
3613 70	He I	6	0 17
3634 35	He I	28	0 40
3657 59	H35, 36	7	0 24
3658 81	H34	7	0 23
3659 28	H33	6	0 22
3660 22	H32	6	0 21
3661 25 .	H31	6	0 21
3662 29 .	H30	6	0.24
3663 4.	H29	6	†
3664 48	H28	6	0 27
3665 93 .	H27	5	0 27
3667 52	H26	5	0 32
3669 27	H25	5	0 31
3671 32	H24	5	0 38
3673 61 .	H23	5	0 42
3676 25	H22	4	0 46
3679 25	H21	4	0 49
3682 74	H20	4	0 60
3686 86 .	H19	4	0 68
3691 49 .	H18	4	0 82
3694 17	Ne II	1	0 37
3697 11.	H17	3	0 99
3702 82	O III	14	0 33
3703 82	H16	3	1 17
3705 02	He I	25	0 70
3707 23	O III	14	0 33
3709 67 .	{O III *Ne II* Ar II ??}	21 1 67	0 07
3711 92	H15	3	1 27
3713 04	Ne II	5	0 24
3714 04	O III	14	0 22
3715 15	O III	14	0 30
3721 90	H14	3	2 32
3726 01	[O II]	1*F*	8 48
3728 73 .	[O II]	1*F*	5 61
3730 85	He I	.	0 02
3732 60	He I	24	0 09
3734 39	H13	3	1 94
3736 62	O IV	6	. . .
3740 24	O II	31	0 06‡
3745 83 3746 37	He I Ar II	4 130	0 03
3750 14	H12	2	2 43
3754 50 .	{N III O III}	4 2	0 52
3757 33	O III	2	0 33

* Wavelengths shortward of this point are RMT wavelengths; longward they are the measured wavelengths

† H29 is blended with mercury from Los Angeles

‡ Wavelength discrepancy between measured and RMT

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TABLE 3—*Continued*

λ	Ident	Mult	I
3759 93	O III	2	1 54
3762 40	Si IV / O II	3 / 31	0 10
3766 48	Ne II	1	0 06
3768 93	He I	65	0 08
3770 63	H 11	2	3 38
3773 08	Si IV	3	0 07
3774 13	O III	2	0 20
3777 16	Ne II	1	0 07
3778 65	S III	5	0 07
3784 91	He I	64	0 04
3791 42 .	O III	2	0 33
3796.36	He II	5	0 10
3797 93 .	H10	2	4 28
3805 96 ..	He I	63	0 05
3811 08	O III	2	0 03
3813 59 .	He II	4	0 11
3819 66	He I	22	1 12
3826 93	Ar II	54	0 02
3829 38	Mg I ??	3	0 03
3831 74	S III	5	0 04
3833 77	He I / He II	62 / 4	0 19
3835 43	H	2	6 15
3838 23	Mg I ?? / *He I*	3 / 61	0 09
3839 83 .	[Fe V]	3*F*	. ..
3851 10	O II	12	0 05
3852 90 .	S II ??	30	0 03
3855 90	Si II	1	0 10
3858 04	He II	4	0 14
3862 52	Si II	1	0 12
3866 68.	.	.	0 04
3868 63 .	[Ne III]	1*F*	100 00
3870 58 .	..	.	0 16
3871 73 .	He I	60	0 08
3882 38	O II	11	0 11
3888 79	*H* / He I	2 / 2	18 9
3891 44	[Fe V]	3*F*	0 11
3895 66 .	[Fe V]	3*F*	0 09
3905 83 .	.	..	0 04
3907.38	O II	11	0 03
3914 90	Ar II ??	2	0 03
3918 91	C II / N II	4 / 17	0 04
3920 52 .	C II	4	0 05
3923 51	He II	4	0 18
3926 56 .	He I	58	0 16
3928 87	S III / Ar II	8 / 10	0 02
3933 19 .	S II ?? / [Fe II] ??	55 / 8*F*	0 03
3935 02	.		0 03
3944 87	O II	6	0 03
3947 99	C II	32	0 05
3954 94	O II	6	0 04‡
3960 72	..	.	0 03
3964 79	He I	5	0 66
3967 40 / 3970 00 .	[Ne III] / H	1*F* / 1	47 5
3973 16	O II	6	0 06
3976 77	O IV	10	0 01
3979 71 .	.		0 02
3982 96	O II	6	0 02
3986 19	S III	8	0 03
3993.06 .	..	...	0 03
3995 04 .	N II	12	0 02
3997 15 ..	[F IV]	1*F*	0 02§
3998 91.....	..	..	0 04
4001 03	.. .	. .	0 02
4003 62	N III	16	0 07
4009 31	He I	55	0 22
4026 15	He I	18	2 10
4035 08	O II	51	0 06
4041 41	O II / N II	50 / 39	0 11
4043 57 . ..	N II	39	0 04
4056 03	C III	24	0 02
4060 22	[F IV] / O II	1*F* / 97	0 04§
4062 91	Ne II / O II	53 / 60	0 05
4068 37	[S II]	1*F*	0 67
4069 96 .	O II	10	0 53
4072 16	O II	10	0 44
4074 05	O III	23	0 06
4075 94	*[S II]* / O II	1*F* / 10	0 58
4080 90	O III	23	0 07
4081 90	N II	38	0 03
4083 86	O II	49	0 11
4085 24	O II	10	0 14
4087 19	O II	48	0 14
4089 18	Si IV / O II	1 / 48	0 30
4092 98 . .	O II	10	0 09
4097 25	O II / *N III*	20, 48 / 1	1 94
4101 67	H	1	26 5
4103 41	*N III* / O II	1 / 20	0 97
4104 90 ...	O II	20	0 10
4107.01 .	O II	47	0 06
4109 82	N II	44	0 03
4110 63 .	O II	20	0 05
4112 55	O II	21	0 04‡
4115 88	Si IV	1	0 03
4119 52 .	O II	20	0 22
4120 85	He I	16	0 24
4123 55 .	[Fe V]	2*F*	0 03§
4125 30	S III	11	0 03
4128 70 .	Ar II ??	....	0 05
4132 66 . .	O II	19	0 10

‡ Wavelength discrepancy between measured and RMT.
§ Identification from Bowen (1960).

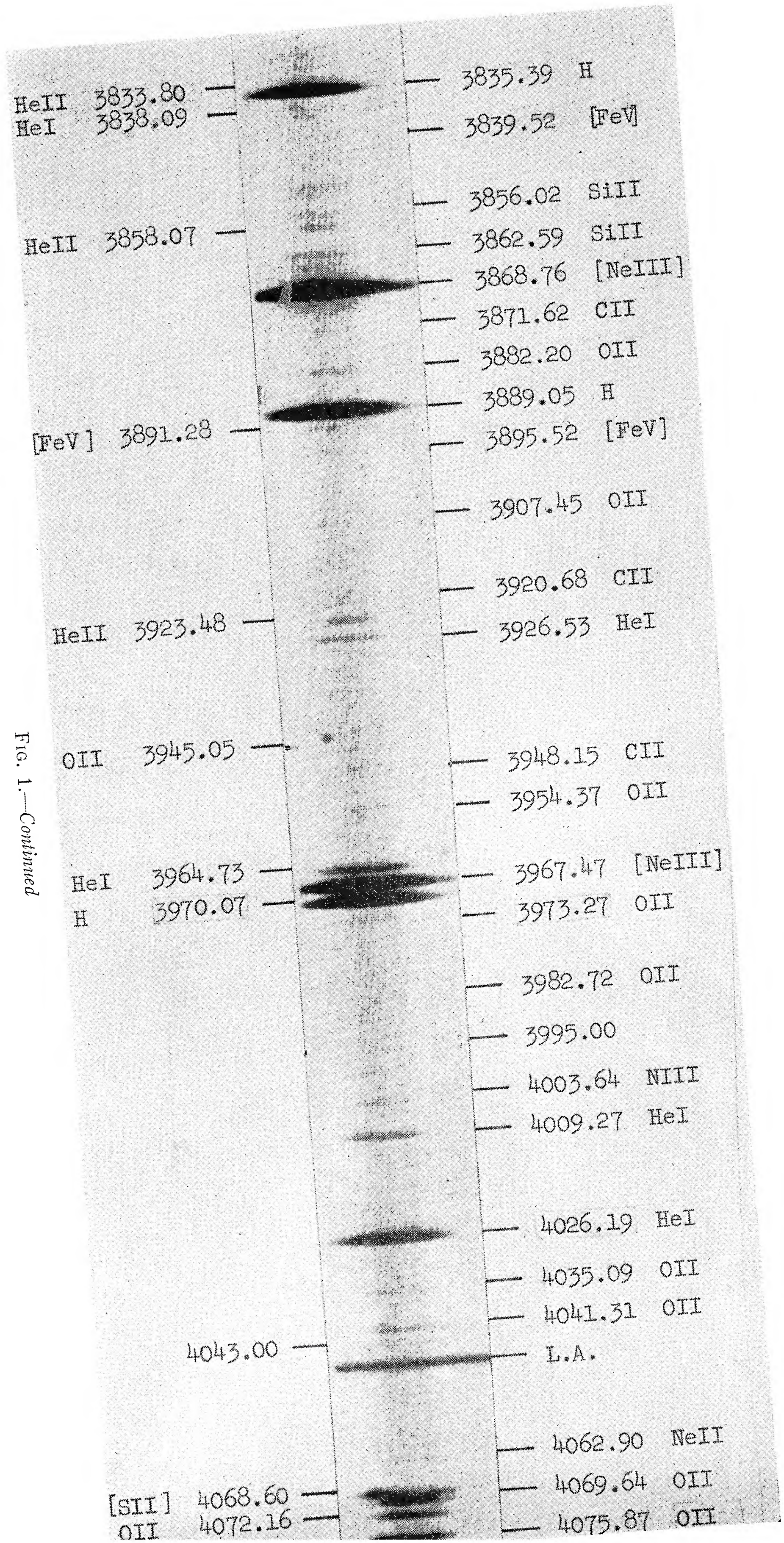

FIG. 1.—*Continued*

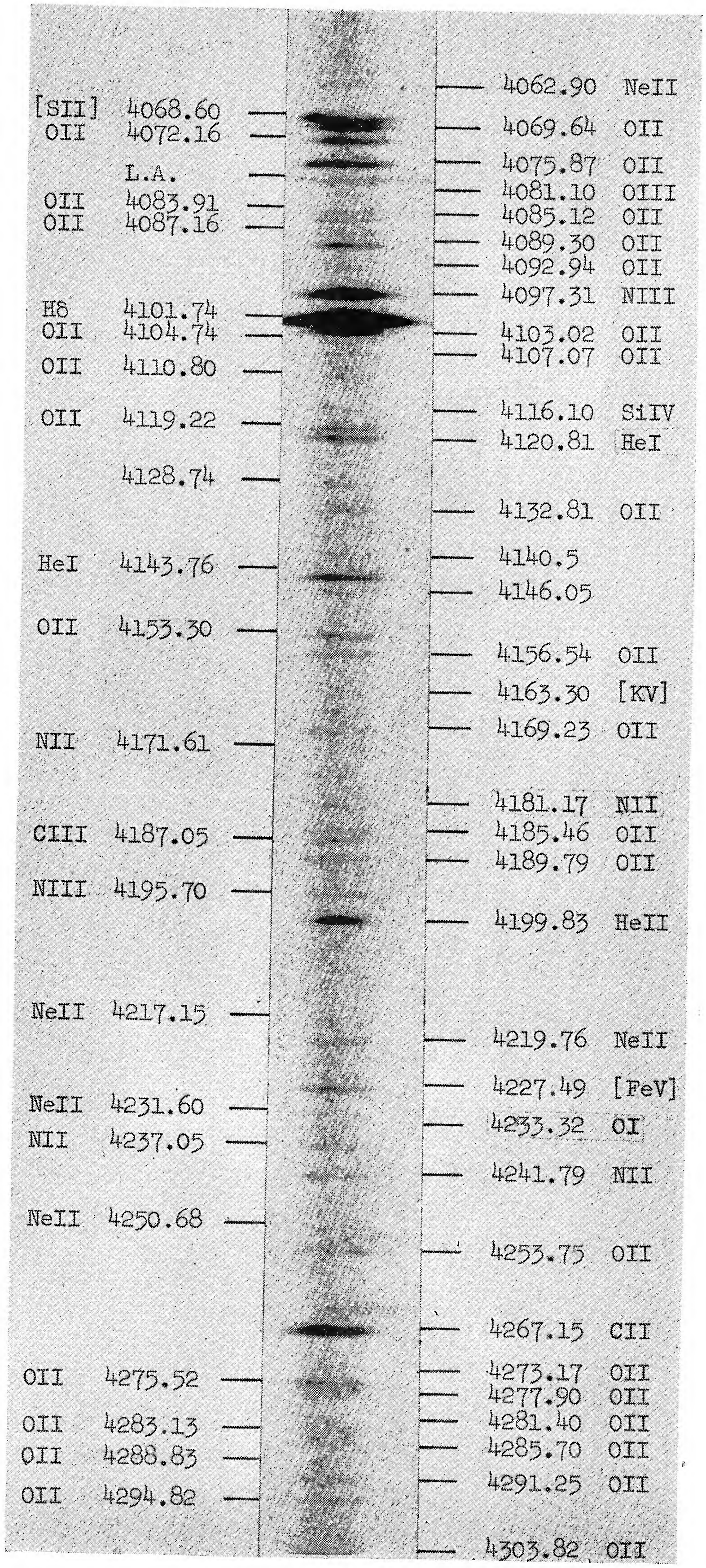

FIG. 1.—*Continued*

TABLE 3—*Continued*

λ	Ident.	Mult.	*I*	λ	Ident.	Mult	*I*
4135 31	. . .		0 03	4333 01	O II	65	0 05
4136 76			0 02	4337 10	O II	2	0 06
4139 94	. .	. .	0 04	4340 42	H	1	49 1
4143 81	He I	53	0 36	4344 51	O II	65	0 09
4146 00	O II	106	0 04	4345 72	O II	2	0 15
4150 56	Ne II	53	0 02	4347 80	O II	16	0 07
4153 66	O II	19	0 16	4349 46	O II	1	0 22
4155 48	O II	19	0 11‖	4351 75	O II	16	0 04‡
4163 12	[K V]	1*F* ?	0 03§	4355 47	. . .	. . . .	0 02
4169 14	O II	19	0 08	4363 16	[O III]	15*F*	7 94
4171 57	N II	43	0 03	4366 97	O II	2	0 16
4176 75	N II	42	0 03	4369 20	O II	26	0 05
4181 15	N II	49	0 04	4371 73	O II	76	0 05
4185 51	O II	36	0 08	4376 67	C II	46	0 05
4186 94	C III	18	0 13	4379 20	N III	17	0 39
4189 78	O II	36	0 11	4387 90	He I	51	0 68
4195 72	N III	6	0 08	4392 00	Ne II	57	0 10
4199 90	He II	3	0 49	4398 02	Ne II	56	0 06
4202 00	Ar II	8, 124	0 02	4400 91	Ar II ??	1	
4215 80	N III	6	0 03	4403 51			. .
4217 20	O I / Ne II	33 / 52	0 03	4408 31	. .		0 06
4219 79	Ne II	52	0 08	4409 42	Ne II	. .	0 10
4222 83	O I	33	. . .	4412 95	Ne II	55	0 05
4225 07	.	. .	0 03	4414 94	O II	5	0 13
4227 44	[Fe V]	2*F*	. . .	4416 94	O II / Ne II	5 / 61	0 11
4231 61	Ne II	52	0 03	4419 98	.		0 02
4233 83	O I	33	0 02	4425 43	. .	. . .	0 02
4237 04	N II	48	0 06	4428 50	Ne II	61, 57	0 24
4241 24	N II	47, 48	0 10‡	4431 09	Ne II	56	0 08
4245 28			0 02	4432 76	N II	55	0 24
4248 84	. .	. .	0 02	4434 87	. .	. .	0 34
4250 53	Ne II	52	0 03	4437 60	He I	50	0 08
4253 88	O II	101	0.09	4439 95	Ne II	61	0 03
4267 11	C II	6	0 03	4442 47	Ne II	56	0 01
4272 88	O II	68	0 03	4446 68	Ne II	56	0 03
4275 57	O II	67	0 20	4448 37	O II	35	0 06
4276 73	O II	54, 67	0 11	4453 29	. .	.	0 03
4277 74	O II	67	0 08	4456 83	Ne II	61	0 04
4281 38	O II	54	0 03	4459 04			0 04
4283 29	O II	54, 67	0 07	4464 25	.		0 03
4285 70	O II	78	0 08	4465 65	O II	94	0 06
4288 80	O II	54	0 04	4471 50	He I	14	6 01
4291 61	C II / O II	41 / 55	0 06	4478 04	O II	88	0 05
				4481 16	Mg II	4	0 04
4294 85	O II	54	0 10	4487 85	O II	104	0 03
4303 89	O II	54	0 18	4489 70	O II	86	0 04
4307 33	O II	53	0 02	4483 23	S II ??	43	. . .
4309 21	Ar II ??	36	0 05	4491 89	O II	86	0 07
4311 50	.	. .	0 02	4495 58	.	. .	. . .
4313 95	C II / O II	28 / 78	0 04	4498 52	Ar II ??	136	0 03
				4504 40	. . .	. .	. . .
4315 36	O II	64, 79	0 04	4510 99	N III	3	0 23
4317 24	O II	2	0 13	4515 08	N III	3	0 08
4319 81	O II	2	0 09	4517 32	C III	9	0 07
4325 83	O II	2	0 10	4521 07	. .	.	0 01
4327 63	O II	11	0 07	4523 65	N III	3	0 08
4331 39	O II	41	0 03	4527 82	N III	13	0 08

‡ Wavelength discrepancy between measured and RMT.
§ Identification from Bowen (1960).
‖ Possible wavelength error, 1 Å too small

TABLE 3—*Continued*

λ	Ident.	Mult.	I	λ	Ident.	Mult	I
4529 7.	O III	32	. . .	4647 40	C III	1	0 32
4530 32	N II	59	0 05	4649 14	O II	1	0 87
4531.96	. .	. .	0 07	4651 35	C III	1	0 35
4534 57	N III	3	0 09	4658 42	C IV	8	. . .
4541.59	He II	2	0 66	4661 64	O II	1	0 30
4544 80	N III	12	0 09	4667 28	N II	11	
4547 34	N III	3	0 05	4671 09	. .	. .	. . .
4552 54	N II	58	. . . .	4673 75	O II	1	0 10
4557.72	. .		0 03	4676 26	O II	1	0 24
4562 66	Ne II	64	0 03	4683 40	Si III	13	0 18
4564 43	Ar II	85	0 04	4685 68	He II	1	18 8
4571.10	Mg I	1	0 13	4698 27	O II	40	. . .
4574 58	Si III	2		4702 . .	O II	58	2 33
4588 6.	. .	. . .	. . .	4705 36	O II	25	.
4590 97	O II	15	0 10	4708 56	O II	89	. . .
4596 17	O II	15	0 08	4711 34.	[Ar IV]	1*F*	5 29
4602 1	O II	93	0 08	4713.17	He I	12	0 64
4609 9.	O II	93,92	0 17	4724 80		. . . .	0 07
4613.30	O II	93		4740 20	[Ar IV]	1*F*	7 40
4621 07	O III	92	.	4782 39	Ne II	71	0 56
4631 10	Si IV	6	. .	4805 06	. .	. .	0 97
4634 16	N III	2	1 56	4861 30	H	1	100 0
4638 85	O II	1	0 05	4921 96	He I	48	0 15:
4640 64	N III	2	2 94	4958 95	.	.	
4641 90	{N III {O II	2} 1}	0 91				

tensities in the λ 3700 region may be 20 per cent in error compared with those in the λ 4700 region. Lines may be compared with their neighbors to a much higher accuracy, but, of course, the weakest lines are subject to large, random, accidental errors. H-intensities past H30 are not reliable due to blending.

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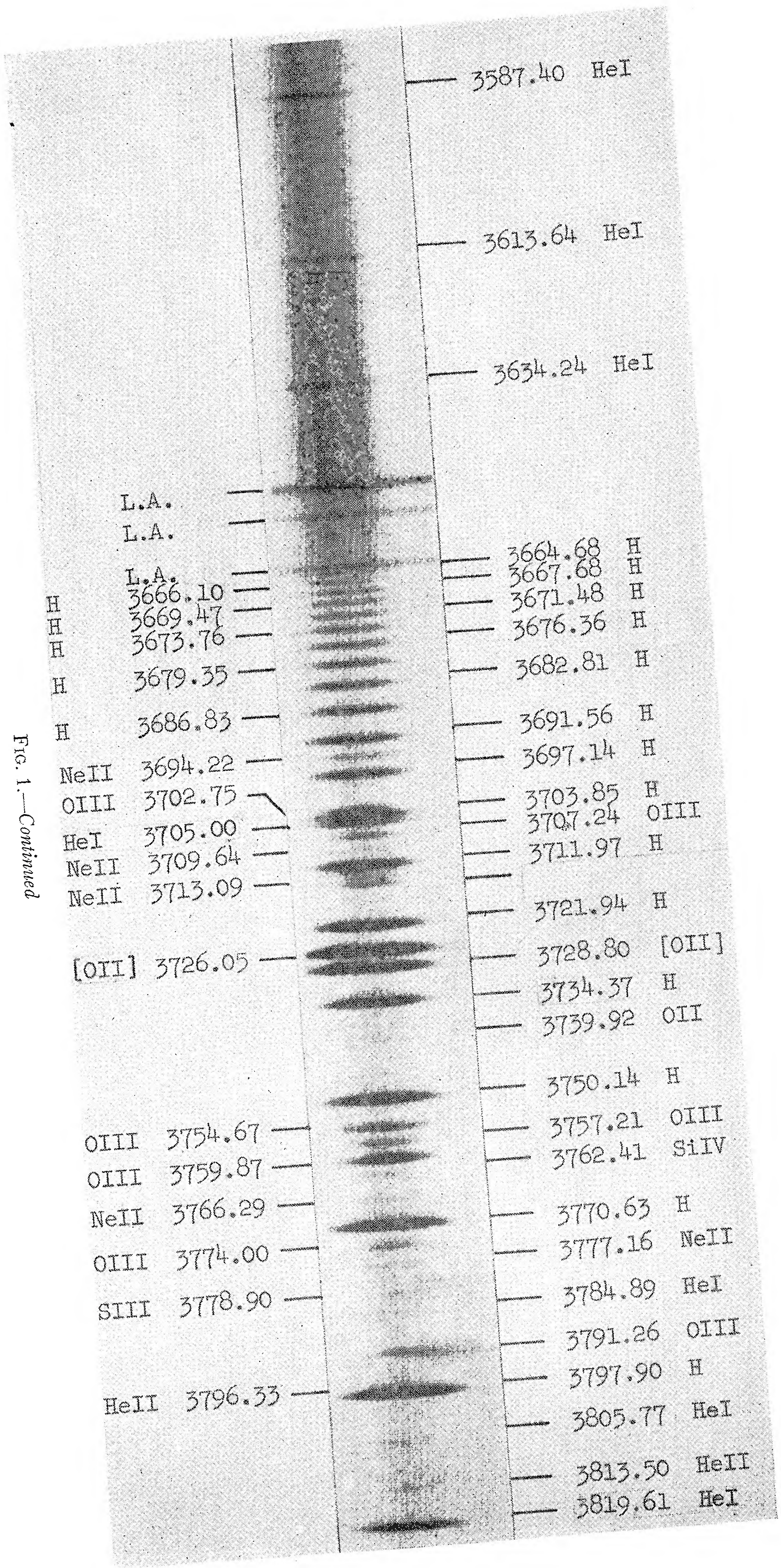

Fig. 1.—*Continued*

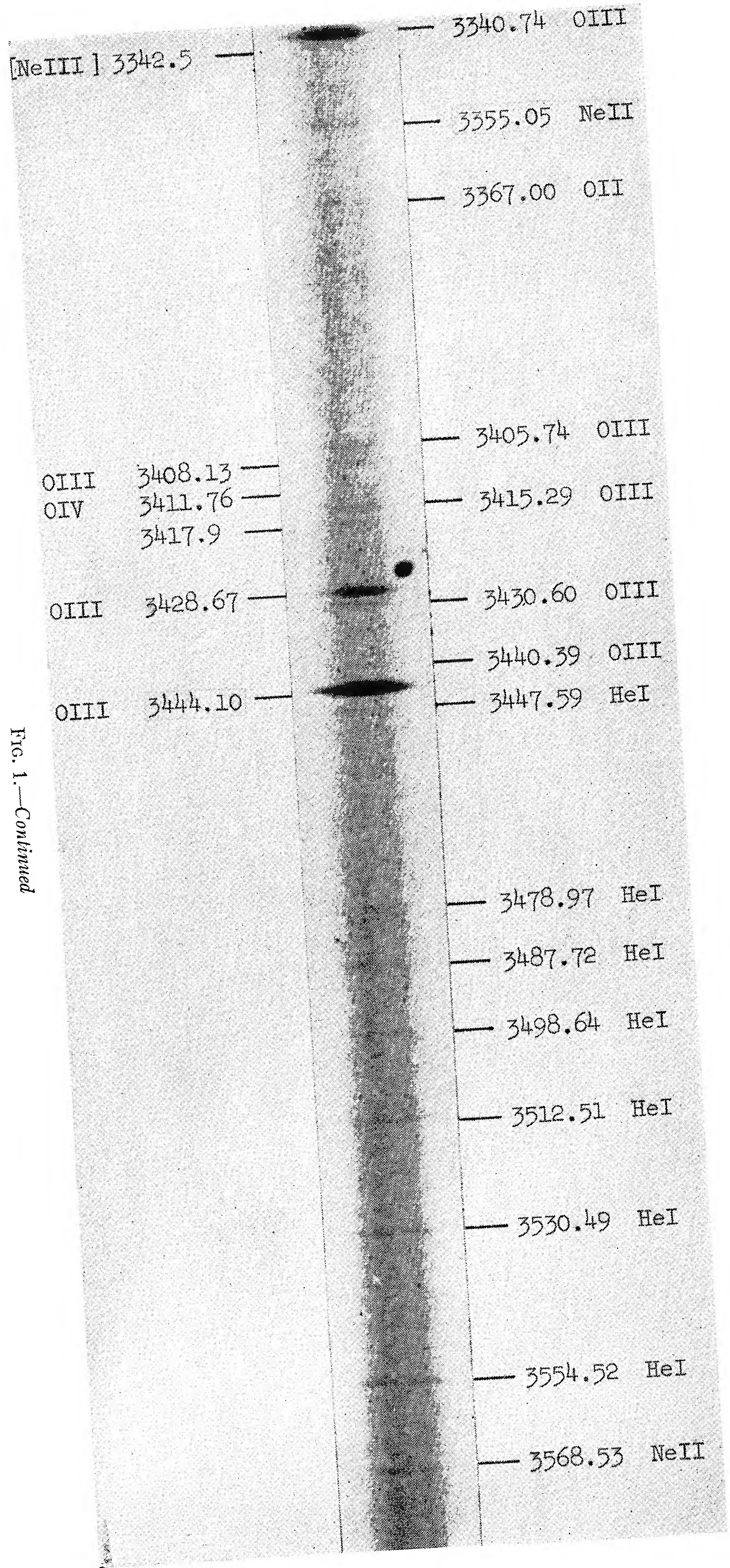

FIG. 1.—*Continued*