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SPECTROPHOTOMETRIC STUDIES OF GASEOUS NEBULAE

VIII. THE IRREGULAR PLANETARY NEBULA NGC 2440

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ABSTRACT

By photographic and photoelectric techniques we have measured emission-line intensities in the spectrum of the irregular, high-excitation planetary nebula NGC 2440 between λ3109 and λ5016 Å to a minimum intensity at peak instrumental sensitivity of 2×10^{-4} $I(H\beta)$. This object shows a wide range of excitation, from [Mg I] to O IV and [Ne V]. Electron temperatures and densities appear to be normal. The electron density in the outer parts of the nebula away from the central condensations is about 10^3 cm^{-3}.

I. INTRODUCTION

The planetary nebula NGC 2440 is one of the more unusual of its class. It is a bright, somewhat elongated object which shows two distinct central condensations with fainter outer filaments. The 200-inch photographs by Minkowski (1964) and the *Palomar Sky Survey* prints show a large faint halo enveloping the object. Isophotic contours have been published by Aller (1956). The nebula exhibits a great range in excitation and thus somewhat resembles NGC 7027. Also, like NGC 7027, no central star is visible under the best conditions at the prime focus of the 120-inch telescope.

Wyse (1942) made a comprehensive study of the spectrum of NGC 2440, but its unfavorable position (low declination in winter skies) makes photometric work difficult. Aller (1951) photographically measured the intensities of the stronger lines from λ5007 to the atmospheric ultraviolet limit. This work was supplemented and extended into the visual region (to λ6700) by Minkowski and Aller (1956). Measurements between λ4340 and λ5007 have been reported by H. Andrillat (1954, 1955). Liller and Aller (1963) used a photoelectric scanner to cover the region λ5007 to λ3340 Å.

From all available [O III] data, and Osterbrock's (1960) value of the [O II] ratio, Kaler (1966) determined an electron temperature of 13400° K and an electron density of 2.95×10^3 cm^{-3} for the central region. In addition, Kaler (1967) predicted the temperature of the invisible exciting star to be about 110000° K. From a theoretical discussion of the then-existing observations Aller (1957) concluded that the nebula had filaments of greatly differing excitation and density.

II. THE OBSERVATIONS

We used a combination of photographic and photoelectric techniques to measure the line intensities presented in this paper. The photographic observations consist of five plates taken either at the prime focus of the Lick Observatory 120-inch telescope with the nebular spectrograph or at the Newtonian focus of the Mount Wilson 60-inch reflector. These observations are presented in Table 1. For the Lick observations the nebular spectrograph equipped with a step filter over the slit and a step-wedge calibrating spectrograph provided the necessary plate density–intensity relationships. The Mount Wilson observations involved the use of a V-slit calibrating spectrograph for this purpose. Spectrograms of standard stars secured with a wide slit sufficed to determine the combined effect of plate sensitivity and reflectivity or transmissivity of the optics for an assumed atmospheric transmission. We measured areas for all satisfactory lines on the tracings. The procedure for the reduction of the photographic observations was as follows.

We first corrected the data from the plate ES 739 to outside the atmosphere employing Popper's (1937) mean atmospheric extinction coefficients for Lick Observatory. Evaluation of optical transmission, plate sensitivity factors involved observations of ϵ Orionis whose energy distribution was adopted as the mean of those given by Oke (1964) and Code (1960). Next we obtained the correction curve for ES 623 by comparing the raw line intensities with the corrected intensities of ES 739.

We reduced measurements of the principal plate, ES 958, to outside the atmosphere with the aid of the combined results of ϵ Orionis and the central star of the planetary nebula NGC 4361 for which a black-body energy distribution corresponding to a temperature of 50000° K was assumed. The procedure is the same as that used for plate ES 959 of NGC 3242 (Czyzak, Aller, Kaler, and Faulkner 1966), due account being taken of differential atmospheric extinction. A number of lines which seemed to be accurately measurable on all plates served to fit the ES 958 data to the averaged line intensities of ES 623 and ES 739.

TABLE 1

THE OBSERVATIONS

Plate	Date	Telescope	Exposure (min)	Dispersion (Å/mm)	Standard
ES 623	Oct. 24, 1963	120-inch Lick	99	60	None
ES 739	Feb. 6, 1964	120-inch Lick	124	60	ϵ Ori
ES 958	Feb. 7, 1965	120-inch Lick	120	120	ϵ Ori, NGC 4361
B 2312	Feb. 10, 1964	60-inch Mt. Wilson	229	80	ϵ Ori
B 2314	Feb. 11–13, 1964	60-inch Mt. Wilson	345	80	ϵ Ori

Oke's extinction data for Mount Wilson served to reduce measurements of plates B 2312 and B 2314 to outside the atmosphere; we again used ϵ Orionis as our standard star. We then fitted the mean of these intensities to the mean intensities derived from the Lick observations, and then took a final average, which represents the adopted intensities on an arbitrary scale as corrected to outside the atmosphere. Since the photographic observations were directed toward the measurement of the fainter lines, strong lines such as Hβ were not observed.

Two series of photoelectric scanner observations, both secured at Mount Wilson, are available. The first series of measurements, made in 1956 by Liller and Aller (1963), employed a photoelectric scanner at the Newtonian focus, while the second series obtained in the winters 1965–1966 and 1966–1967 used the Cassegrain scanner at the 60-inch telescope. We secured observations both by conventional scanning methods at a slow speed and by making settings on the stronger lines and neighboring continuum. We used both a conventional potentiometer and a pulse counting system. The data from these two second series sets of measurements were in good accord, although they were not in good agreement with the 1956 observations. We attribute this discordance to

TABLE 2

Spectrum of NGC 2440

λ	ID	Mult	$λ_R$	I	I_P	I_{PEP}
5015 7†	He I	4	15 7			. . .
*5007	[O III]	1F	06 9			1502
*4959	[O III]	1F	58 9			509
4930 6	[O III]	1F	31 0	0 15		
4921 9	He I	48	21 9	0 37		. . .
*4861 3	Hβ	.	61 3			100
4740	[Ar IV]	1F	40 2			7 5
	[Ne IV]		25 6			
4724	[Ne IV]		24 3	1 23		
	[Ne IV]		24 1			9 7
	He I	12	13 1			
4712 6	[Ar IV]	1F	11 3	5 04		
4686	He II	1	85 7	. . . .		58 6
4676 1	O II	1	76 2	0 071		
4658 3	C IV	8	58 6	0 58		
4649 9	C III	1	50 2			
4648 9	O II	1	49 1	0 45		
4647 5	C III	1	47 4			8 6‡
*4640 6	N III	2	40 6			
4636 7		.	. .	8 39	0 93	
4635 2	N III	2	34 2			
4626 0	C II	49	25 7	0 07		
4620 2	. .	. .	. . .	0 05		
4607 0	[Fe III]	3F	07 1	0 69		
4571 2	[Mg I]	1	71 1	0 17		
4562 0	.		.	0 08		
*4541 .	He II	.	.	3 1		3 0‡
4534 8	N III	3	34 6	0 06	. .	
4522 8	N III	3	23 6		08	
4519 2	N III	3	18 2		18	
	C III	9	16 9		. .	
4515 9	C III	9	16 0		15	
	N III	3	14 9	0 65		
	[K IV]	2F	10 9		. .	
	N III	3	10 9		0 24	
4511 5	Ne II?	70	11 4			
	Ne II?	70	11 3			
4471 7	He I	14	71 5	3 1		3 2‡
4452 6	O II	5	52 4	0 11		
4446 0	Ne II	56	46 5	0 06		
4435 8			. .	0 05		
4421 0	Ne II	66	21 4	0 02		
4417 1	O II	5	17 0	0 05		
4414 7	O II	5	14 9	0 02		
*4387 9	He I	51	87 9	0 29		
4384 1	Ne II?	60	84 1	0 06		
4379 1	N III	17	79 1	0 32		
4363 .	[O III]	2F	63 2	18 0		22 3§
4349 3	O II	2	49 5	0 04		57 3
*4340	Hγ		40 5	28 8		35 0§

* Line used as wavelength standard.
† Line blended with third-order λ3444 of O III
‡ Lines used to find scale factor between photographic and photoelectric intensities
§ Denotes the individual photoelectrically measured intensities of λ4363 of [O III] and λ4340 (Hγ).

TABLE 2—*Continued*

λ	ID	Mult	λ_R	I	I_P	I_{PEP}
4319 5	O II	2	19 6		0 03	
	C II	28	18 9		0 03	
4317 3	O II	2	17 1	0 09	.	
	C II	28	17 4		. ..	
4314 1	C II	28	13 5		0 03	.
4311 5	O II?	79	12 1	0 03		
*4267.2	C II	6	67 3	0 38		
4241 2	N II	47,48	41 8	0 03		
4237 5	N II	48	37 0	0 05	. .. ..	
4230 6	.. ..	.	.. .	0 26	0 05	
4227 4.	[Fe V]	2F	27 5		0 21	
*4199 8.	He II	3	99 8	1 33	.	
4195.9.	N III	6	95 7	0 08		
4186 6	C III	18	87.1	0 20		
4175 8.	..	..	....	0 04	.... ..	
4169 5.	O II	19	69.2	0 05	0 02	
4166 8	. .. . .	.....	. .. .		0.03	.
4163.3.	[K V]	1F	63 3	0 15	..	
4156.4. .	C III	21	56 5	0 03	. ..	
	O II	19	56.5	....		.
4153 1.	O II	19	53 3	0 03		
4143 8	He I	53	43 8	0 27		
4133 5	O II	19	32 8	0 05		
4128.1.	... . ..	. ....	. ... ..	0.04	. ..	
4121.4.	[K V]	. ..	22 6	0 29	0 16	
	He I	16	20.8		....	
4119.4...	O II	20	19 2		0 13	. .. ..
4101.7...	Hδ	......	01.7	14 9	. ...	21.7‡
4097....	N III	1	97.3	2.40		
*4076 4	[S II]	1F	76 4	3 25	0.73	3 8
4072 ..	O II]	10	72 2		0 12	
4068 6	[S II]	1F	68.6		2 40	
4059 7.	[F IV]	1F	60 2	0 07		
4050 3	.	..	.. . .	0 03	.	
4026.2	He I	18	26 4	1 74	. ..	. .
4009 6	He I	55	09 3	0 14	0 07	.
4008 2	[Fe III]	4F	08 4		0 07	
4003 5	N III	16	03 6	0 08		
3999 0	N III	16	98 7	0 06		
3995.2	O IV	10	95 2	0 05		
3970 .	H7	. .	70 1	21 7		34 8
3967	[Ne III]	1F	67 5			
3964 .	He I	5	64 7	0 69		
3956 7	O IV	10	56 8	0 03		
3947 7	C II	31	47 6	0 08		
3944 8	O IV	10	45 3	0 05		
3926 3	He I	58	26 5	0 10		
*3923 5	He II	4	23 5	0 55		
3905 5	Si I	3	05 3	0 08		
3889 .	H8	.	89 1	10 4		8 0
	He I	2	88 7			
3868 .	[Ne III]	1F	68 8	20 4		81 9
3862 5	Si II	1	62 6	0 16		
	O II	12	63 5			
*3858 1	He II	4	58 1	0 43		
3850.8	O II	12	51 0	0 07		
	O II	12	50 8			
3835 .	H9	....	35 4	6 4		5 0‡
*3819 3	He I	22	19 6	0 74		.. ..
3813 5..	He II	4	13 5	0 46		...

TABLE 2—*Continued*

λ	ID	Mult.	λ_R	I	I_P	I_{PEP}
3806 0 .	He I	63	05 8	0 03	.. .	... .
3803 6	O II	34	03 1	0 03		
3797 9	H10	....	97 9	4 39		
3791 3	O III	2	91 3	0 32		
3781.7	He II	5	81 7	0 24		
3774 0	O III	2	74.0	0.33	..	
3770.6	H11	...	70 6	2 72	. .	.
3759 9	O III	2	59 9		3 19	
3757 .	O III	2	57 2	4 47	0 33	5 6
3754 7	O III	2	54 7		0 95	
3750 2	H12	..	50 2	2 37	......	
3741 0	O II	31	39 9	0 05	.	
3736 .	O IV	6	36 8	2 37	0 46	
3734	H13	..	34 4		1 91	
3729	[O II]	1F	28 8	25 2	.	
3726..	[O II]	1F	26 1	33 6		
3721 8	H14	..	21 9	2 51		114
	[S III]	2F	21.7			
3715	O III	14	15 1	0 23	. ..	
	O III	14	14 0			
3712 1	H15	....	12 0	1 55	.. ..	
3707 .	O III	14	07 2		0 28	
3705	He I	25	05 0	2 04	0 50	
3704	H16	..	03 9		1 26	
*3697.	H17		97 2	1 12	.	
3691.	H18		91 6	1 05		
3686	H19		86 8	1 02		
3682	H20		82 8	0 89		
3679	H21		79 4	0 76		
3676	H22		76 4	0 66		
3674 .	H23	.	73 8	0 48		.
3653 0	He I	27	52 0	0 25		
3634 5	He I	28	34 2	0 31		
3623 1	.	.	... .	0 15		
3614 1	He I	6	13 6	0 10		
3608.7	C III	10	09 6	0 06		
	C III	10	09 0			
3586 8	He I	31	87 4	0 30		
3568 0	Ne II	9	68 5	0 18		
*3554 4	He I	34	54 4	0 27		.
3530 9	He I	36	30 5	0 06		
3499.8	O II?	80	00 5	0 26		
3487.6	He I	42	87 7	0 21		
3483 3	N IV	1	83 0	0 21		
3479 1	N IV	1	78 7	0 37		
	He I	43	79 0			
3466 0	[N I]	2F	66 4	0 61		
3443 9.	O III	15	44 1	. ..		
3432 7	O IV	8	33	0 32		
	[Ne V]	1F	25 9			95.8
3425 9	O III	15	28 7	..		
	O III	15	30 6			
3414 7	O III	15	15 3	0 30	. . . .	... .
3411 0	O IV	2	11 8	0 94	0 55	.
3409 1	O IV	3	09 8		0 39	. .
3403 6	O IV	2	03 6	0 63	. . . .	... ...
3385 2	O III	27	85 0	1 38	0 55	. .
	O IV	3	85.6			
3380 5	O IV	3	81.3		0 83	....

TABLE 2—*Continued*

λ	ID	Mult	λ_R	I	I_P	I_{PEP}
3362 4	{O IV O III	3 22	62 6 62 4	0 32		
3342 .	[Ne III]	2F	42 5	. .		36.2
*3340 7	O III	3	40 7	7 9		
3312.3	O III	3	12 3	6 2		
*3299 4 .	O III	3	99 4	2 9		
3291 0	O II	23	90 1	0 28		
3287 7 .	O II	23	87 6	0 20		
3240 9 .	[Na IV]	. . .	41 7	1 44		
3233 5	S III	3	33 2	0.87		
3231 5	S III	3	31 1			
*3203 1 .	He II	1	03 1	19 7		
3187.4 .	He I	3	87 7	3 48		
3181 8	. . .	. .	. . . . .	0 80		
*3132 9 . .	O III	12	32 9	22 9		
3121 2	O III	12	21 7	0 70		
3109 0.	[Ar III]	2F	09 0	0 84		

differences in judgment in drawing in the position of the background which consists both of a true continuum and weak lines. Accordingly we have used primarily the data for the stronger lines to calibrate the photographic data. For these measurements, ξ_2 Ceti, ϵ Orionis, and θ Crateris have served as comparison stars (see Oke 1964).

The comparison of the photographic and photoelectric data sufficed to find the final scale factor which allowed us to reduce the photographic line intensities to the usual scale I Hβ) = 100.

All of the Lick observations were carefully guided with the slit set in position angle 44°, i.e., along the extensions depicted in Curtis' (1918) photograph of this object. On plate ES 623 we made tracings at four different points in addition to the central region. At these points of lowered surface brightness we were able to measure the $I(\lambda 3729)/I(\lambda 3726)$ ratio of [O II].

We give the results in Table 2. The first column gives the wavelength as measured on the tracings. For the permitted lines, the second, third, and fourth columns give the identification, multiplet number, and laboratory wavelength (the first two digits, being the same, have been suppressed), respectively, as found in Miss Moore's (1945) Revised Multiplet Table (RMT). For the forbidden lines, the second and fourth columns give, respectively, the identification and wavelength as given by Bowen (1960) and the third column gives the RMT multiplet number. The fifth column gives the mean adopted photographic intensity, corrected to outside the atmosphere. Since the plates were of moderate dispersion, blending of lines was a serious problem. As can be seen from Table 2, the blended intensity of two or more lines is often given. In many cases, however, the heights of the individual lines in the blend can be used to allow us to interpolate their intensities. These estimated intensities, called I_P, are given in the sixth column. The seventh column gives the photoelectrically measured intensities.

Table 3 gives the intensities of various strong lines in different points in the nebula as measured from the plate ES 623.

The principal plate, ES 958, is reproduced in Figure 1 (Plates 7 and 8) with identifications for the important lines.

III. DISCUSSION

We have identified permitted lines of the following spectra: H, He I, He II, C II, C III, C IV, N II, N III, N IV, O II, O III, O IV, Ne II, Si I, Si II, and S III. The forbidden lines

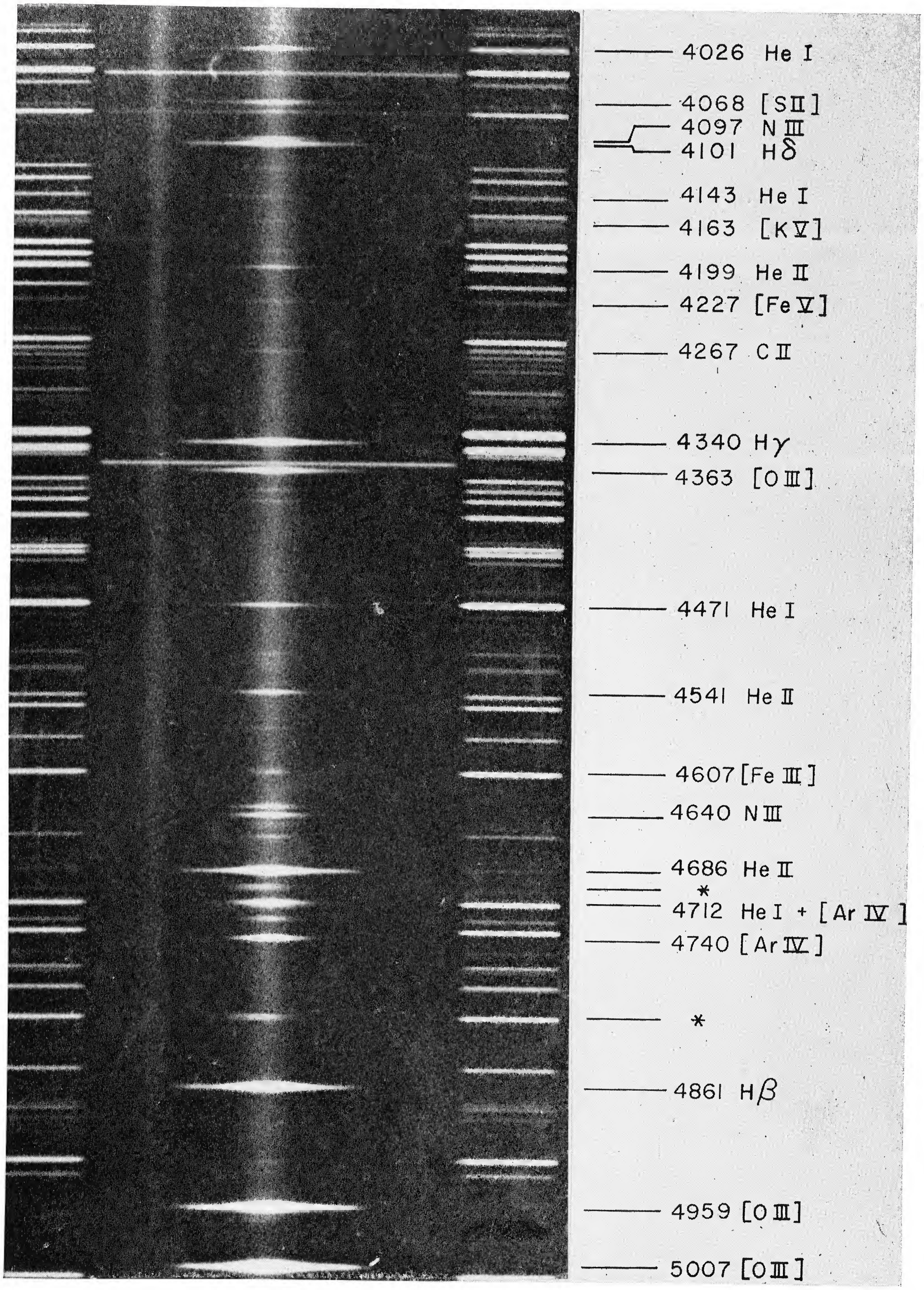

FIG. 1.—The spectrum of NGC 2440. The asterisk (*) denotes third-order lines of λ3132 and λ3203

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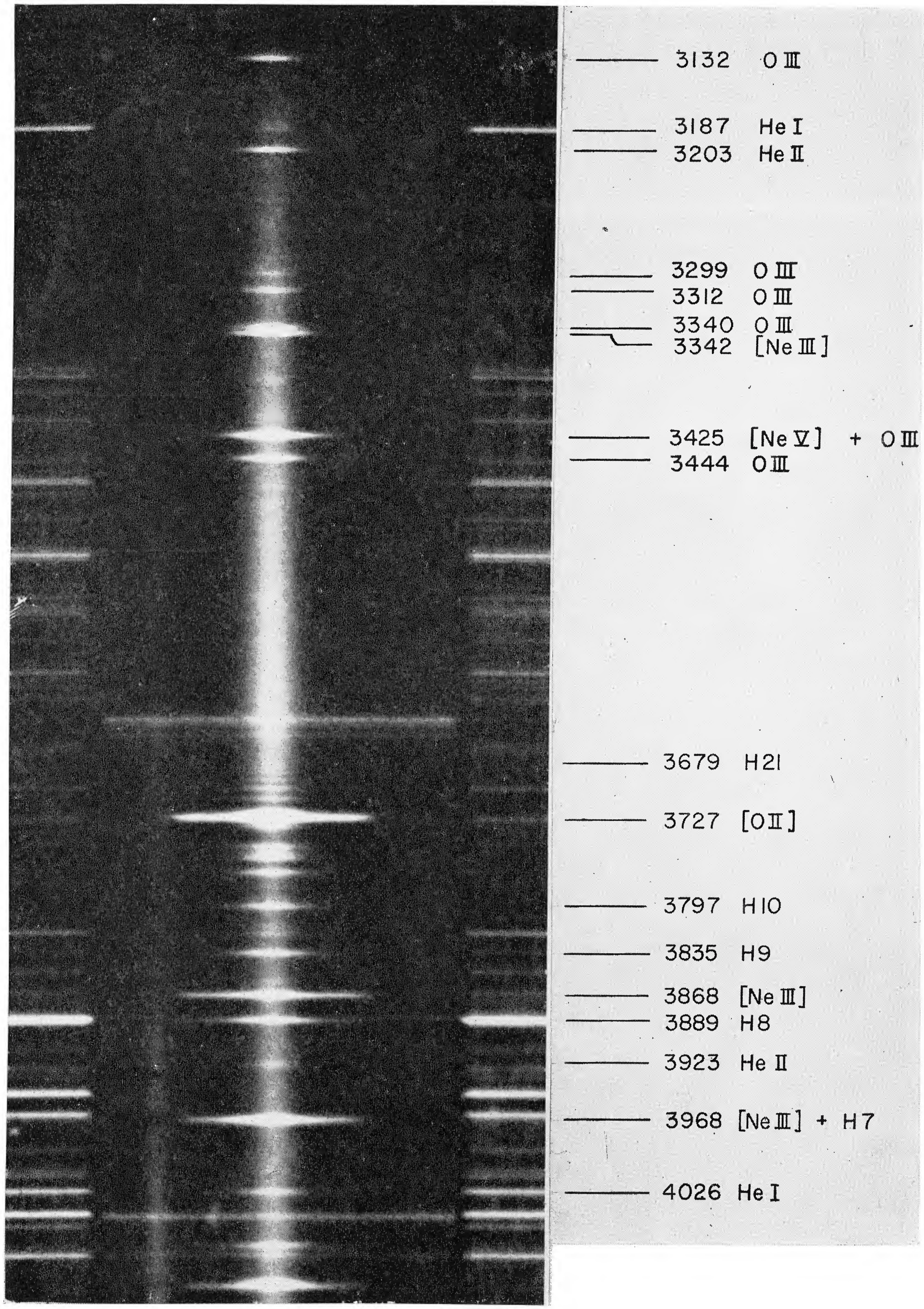

FIG. 1—*Continued*

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are represented by [N I], [O II], [O III], [F IV], [Ne III], [Ne IV], [Ne V], [Mg I], [Na IV], [S II], [Ar III], [Ar IV], [K IV], [K V], [Fe III], and [Fe V]. Note the wide range in excitation. The [Mg I] line is probably excited by electron collision. Except for the O III and N III lines produced by the Bowen fluorescent mechanism (Bowen 1934), the permitted lines are probably due to recombination.

We have been able to determine the electron density at four points in the diffuse amorphous region away from the center of the nebula. The electron density of this region is fairly uniform to nearly 19″ out along the major axis, at about 10^3 cm^{-3}, and falls to a minimum of about 600 cm^{-3} about 14″ northeast of the center. Compare these values with $N_e = 2.95 \times 10^3$ cm^{-3} as found from the observations of Osterbrock (1960) for the central region.

If we compare the 10-cm radio flux (Thompson, Colvin, and Stanley 1967) with O'Dell's (1963) Hβ flux, we obtain a reddening constant of 0.56. We then derive an electron temperature of 13500° K from the [O III] line intensities.

TABLE 3

SPECTRUM OF THE OUTER REGIONS OF NGC 2440

[I(Hβ) of Center = 100]

λ(Å)	ID	I 14″ NE	I 14″ SW.	I 19″ NE	I 19″ SW.
4363	[O III]	1 09	0 40	0 78	0 44
4340 .	Hγ	2 21	1 01	1 35	0.88
4101	Hδ	0 84	0 34	0 65	0 44
3970 ..	H7	0 36	0 30	0 92	0 19
3968	[Ne III]	0 69	0 71	0 34	0.48
3889 .	H8+He I	0 58	0.27	0 44	0 18
3868 .	[Ne III]	3 15	2 19	3 92	1 66
3729.	[O II]	1 24	2 35	3 85	2 35
3726.	[O II]	1 08	2 59	4 18	2 60

As usual, the accuracy of the results is difficult to determine. There are three points to consider: the accuracy of intensity ratios of lines of moderate to strong intensity taken from different parts of the spectrum, the accuracy of the faint lines, and the scale factor to fit the photographic observations to the very strong lines, e.g., Hβ. By moderately strong lines we mean those relatively unaffected by plate grain, e.g., those with $I > 0.7$ at λ4000, > 1.5 at λ3400. From the scatter of the line ratios taken between plates, the over-all internal accuracy for these lines appears to be about ± 10 per cent. The accuracy of intensity ratios for lines close to one another is of course greater than for those widely separated in the spectrum.

The fainter lines are affected by plate grain and are sensitive to the placement of the continuum. The very faintest lines measured are subject to large random errors, probably up to a factor of 2. This situation appears to be worst in the ultraviolet shortward of the Balmer limit. The noise level of the plate grain is higher here, and the plate + instrument sensitivity + atmospheric transmission is falling off. It is in this region also that the average extinction coefficients are poorest and subject to greatest night to night error.

Outside of the signal-to-noise ratio, the over-all accuracy depends on the accuracy of the correction to outside the atmosphere as derived from standard star observations. It is very encouraging to note that plates calibrated and corrected independently with different instruments give line intensities of lines which are accurately measurable (i.e., on the straight part of the characteristic curve) to within 10 to 20 per cent of one another.

The scale factor to put all the intensities on the scale I(Hβ) = 100 provides a different problem, as there is not a great deal of overlap between the photographic and photoelectric intensities. The five lines which are used for comparison are distributed between λ4550 and λ3700, and give scale factors which show a mean percentage deviation of 8 per cent. In addition, the final results in the ultraviolet are for the most part consistent with the data of Aller (1951). There are actually thirteen lines which overlap between the photographic and photoelectric observations. As can be seen from Table 2, the agreement is not always good. There appears to be a systematic error of the photographic/photoelectric ratio which is a function of wavelength, and which has an amplitude of about 20 per cent of the intensities. We believe that this systematic error is actually spurious and that the error is caused by stratification effects within the nebula. The photoelectric observations include all of the light of the nebula, whereas the photographic observations are made with a slit spectrograph which selects only a small part of the nebular light, generally near the center. Thus if stratification of ions exists within the nebula, the line intensities will not always agree. This effect will even enter into the comparison of two slit spectrograms, as the spectrograph and/or microphotometer slit will not always be set exactly on the same place within the nebula. Note particularly the disagreement between the photoelectric and photographic intensities of the lines of [O II] and [Ne III]. This problem is discussed more fully in Paper VII of this series (Aller, Kaler, and Bowen 1966).

There is considerable disagreement between the present photoelectric measurements and those of Liller and Aller (1963). Possibly these discordances arise from differences in assessing the background contribution. In any event, the Mount Wilson 60-inch Cassegrain scanner observations, secured on different nights, yield a consistent series of values which we have adopted. The wavelengths given in the first column of Table 2 are generally good to between 0.2 and 0.5 Å.

We express our gratitude to Director Horace W. Babcock of Mount Wilson and Palomar Observatories for giving us the opportunity to work on this problem with their 60-inch telescope. This study was supported by Air Force office of Scientific Research grant 83-65 to the University of California, Los Angeles; trips to Lick Observatory to secure observations were financed from NASA grant Nsg 237-62. We would also like to express our appreciation to the National Science Foundation for partial support of this work under NSF grants GP 6559 to the Ohio State University and GP 4928 to the University of Illinois. We have also used the facilities of the General Physics Laboratory, Aerospace Research Laboratory, at Wright Patterson Air Force Base, Ohio. We are grateful to Mrs. Rhonda Duvall and Mrs. Frances Murray, General Physics Laboratory, and to Mr. Victor Broquard, University of Illinois, for their help in reducing some of the data from the photoelectric scans and spectral tracings, and to Dr. A. R. Thompson for communicating the 10-cm radio results in advance of publication.

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