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SPECTROPHOTOMETRIC STUDIES OF GASEOUS NEBULAE

III. THE LOW-EXCITATION RING PLANETARY IC 418

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ABSTRACT

Plates taken at the coudé and prime foci of the Lick 120-inch and at the Mount Wilson 100-inch coudé are combined to yield line intensities in the region λλ 3100–5000 Å for the bright, compact, rather regular nebula, IC 418. Line intensities are given both for the bright hydrogen ring and for a strip through the center of the nebula to show the effects of stratification. Average intensities that should approximate those of the integrated light of the nebula are also given. Intensities of emission lines from the central star have been measured and compared with the results of earlier work.

I. INTRODUCTION

Most theoretical work on the spectra of gaseous nebulae has been devoted to discussions of physical processes occurring within an "average" volume element, since for most planetary nebulae published line intensities refer to the integrated light of the nebulae. For some objects, however, it is possible to measure intensities at specific points and to assess stratification effects. Unfortunately, most planetaries have such complicated structures that it is difficult, if not impossible, to infer a plausible three-dimensional structure from a two-dimensional projection.

Fortunately, the bright, low-excitation elliptical planetary nebula IC 418 is sufficiently symmetrical that there is some hope of deriving the radial distribution of the ions from the intensity distributions across the monochromatic images (Wilson and Aller 1951). The Balmer, λ 3727 [O II], and [N II] emissions are concentrated in the outer ring, while [Ne III] and [O III] radiations are strongest in the inner portion. Thus the O^{++} ion distribution simulates the distribution of Ne^{++++} in planetaries of high excitation. Wilson (1950, 1958) found that the internal motions followed the characteristic pattern in that ions of higher excitation (in this instance ions of O^{++}) showed the smallest expansion rates.

Some of the earliest spectrophotometry on this object was done by Aller (1941) who measured the relative intensities of the brightest lines and the Balmer continuum corrected to outside the atmosphere. From these data, Menzel and Aller (1941) calculated the electron density. Menzel, Aller, and Hebb (1941) used the ratio of the intensities of λ 4959 and λ 5007 to that of λ 4363 of [O III] to find the electron temperature. The most extensive work was by Wyse (1942) who gave calibrated eye estimates of the brighter lines from λ 3700 to λ 6755 corrected to outside the atmosphere. Using the Curtis Schmidt telescope of the University of Michigan, and an objective prism, Liller and Aller (1954) measured the intensities of the strongest lines, λ 4959 and λ 5007 of [O III], and Hβ with a photoelectric photometer. From this and the earlier work of Aller (1941) they derived log $N_\epsilon = 4.20$, $T_\epsilon = 18,300°$ K. In 1956 they measured relative line intensities with a spectrum scanner at the Newtonian foci of the 60-inch and 100-inch telescopes at Mount Wilson (Liller and Aller 1963), covering a range of from λ 3727 to λ 5007. O'Dell (1963) used the same telescope but a Cassegrain scanner and an improved infrared cell.

II. REDUCTION AND RESULTS

The reduction technique used for this object differs from that of the earlier papers of this series in that, in addition to photoelectric measurements, we used a star of known energy distribution (BD+28°4211) to obtain plate sensitivity plus instrument transmission plus atmospheric extinction calibrations for the spectrograms. Table 1 lists four plates of the nebula and two of the comparison star that were used.

Plate EC 2439 was taken with the central star drifted along the slit; the other three plates are of the bright ring of the nebula only.

First, we used the density $-\log I$ curves to obtain spectral-line intensities uncorrected for the wavelength-dependent effects of atmospheric extinction, transmission of the optics, and plate sensitivity. Calibration strips are impressed directly on the plate for the Lick coudé spectrograms EC 2437, EC 2438, and EC 2439, while the prime-focus nebular spectrograph plates EC 626 and EC 627 are calibrated with a photographic step wedge. A wedge-slit device provided the calibration for the Mount Wilson coudé plate Ce 14773.

Evaluation of the wavelength-dependent factors operating on EC 2438, EC 2439, and ES 627 followed from measurements of plates EC 2437 and ES 626 of BD+28°4211, which we assumed to radiate as a black body at 50000° K (J. B. Oke, unpublished. This number is quoted in Popper and Walker [1963]). To correct for effects of differential

TABLE 1

OBSERVATIONS OF IC 418

Plate No.	Object	Date	Exposure	Telescope	Focus
ES 627	Nebula	Oct. 25–26, 1963	$33^m.5$	120-inch	Prime
ES 626..	Star	Oct. 25–26, 1963	$8^m.5$	120-inch	Prime
Ce 14773	Nebula	Sept. 3, 1961	261^m	100-inch	Coudé
EC 2439	Nebula	Oct. 26–27, 1963	82^m	120-inch	Coudé
EC 2438	Nebula	Oct 26–27, 1963	210^m	120-inch	Coudé
EC 2437	Star	Oct. 26–27, 1963	62^m	120-inch	Coudé

atmospheric extinction between the star and the nebula, we adopted mean absorption coefficients measured by D. M. Popper (private communication) for Lick Observatory. Thus, intensities of ES 627 differed from those of EC 2438 only by a constant factor. The intensities measured on EC 2439 also differed by a constant factor from those gotten from EC 2438 except for certain lines concentrated in the inner part of the nebula. These scale factors were found by direct comparison with EC 2438 and applied to bring all intensities to the scale of this plate.

We next took a preliminary average of the spectral-line intensities from the two plates ES 627 and EC 2438 and compared these intensities to those of Ce 14773 to draw a calibration-curve to correct them to outside the atmosphere. We now adopt three sets of intensities. One is an average of the intensities from ES 627, EC 2438, and Ce 14773, which is appropriate to the bright ring. Another is the set derived from EC 2439, which takes in a strip across the nebula and includes the inner portions of the nebula as well as the ring. The third is an average of all four plates which is appropriate to the relative intensities in integrated light as measured photoelectrically. In order to find a scale factor to get these line intensities on to the usual scale of $H\beta = 100$, the lines from this last set were compared with the photoelectric results of O'Dell (1963). This same scale factor was then applied to all three sets of intensities.

The results are given in Table 2, which presents the wavelength, identification, and multiplet number of the line in the first three columns, as found in the *Revised Multiplet Table* (Moore 1945). In the case where no identification is given, the wavelength of the line was taken directly from the tracing. The last three columns give the three sets of intensities described above.

TABLE 2

THE SPECTRUM OF IC 418

λ	Ident.	Mult	*I* (Ring)	*I* (Strip)	*I*
5015 7	He I	4	0 74	0.70	0 72
4921 9	He I	48	0 60	0 66	0 62
4861 3	Hβ	1	100	100	100
4781 2	N II ?	20	0 08	.	0 08
4779 7	N II ?	20	0 11	...	0 11
4768.2	....	....	0 11	...	0 11
4713 14	He I	12	0 57	0 60	0 58
4685 7*	He II	1	...	0 41	...
4658 6*	C IV	8	....	0 31	..
4651 4*	C III	1	.	0 54	....
4650 2*	C III	1			
4647 4*	C III	.....	..	0 70	....
4643 1*	N II	5	....	0 26	.....
4641 9*	N III	2	...	0 75	.....
4640 6*	N III	2			
4634.2*	N III	2	....	0.37	....
4630 5	C II / N II ?	49 / 5	0 09	...	0 09
4571 1	Mg I	1	0.52	0 29	0 46
4471 5	He I	14	2 87	3 47	3 17
4437 5	He I	50	0 11	...	0 11
4387 9	He I	51	0 66	0.54	0 63
4368 2	C II	45	0 16	...	0 16
4363 2	[O III]	2F	0 93	0 97	0 94
4342 7	O II	103	0 08	...	0 08
4340 5†	H	1	...	...	40 7
4337 1	O II	2	0 10	...	0 10
4325 7*	C III	7	...	0 14	...
4267 3	C II	6	0 59	0 70	0 61
4267 0	C II	6			
4153.3	O II	19	0 06	...	0 06
4143 8	He I	53	0 35	0 44	0 37
4131 8	Ar II ?	32	0 07	...	0 07
4128 5	Ar II ?	...	0 05	...	0 05
4120 8	He I	16	0 24	0 29	0 26
4120 0	He I	16			
4116 1*	Si IV	1	..	0 45	...
4101 7†	Hδ	1	....	...	20 2
4088 9*	Si IV	1	...	0 39	...
4076 2	[S II]	1F	0 81	0 58	0 75
4072 2	O II	10	...	0 39	0 39
4068 6	[S II]	1F	2 00	1 47	1 87
4026 4	He I	18	1 82	2 00	1 86
4026 2	He I	18			
4009 3	He I	55	0 21	0 38	0 25
3970 1†	H	1	...	...	13 6
3967 5	[Ne III]	1F	0 85	1 47	1 00
3964 7	He I	5	1 08	1 37	1 16
3926 5	He I	58	0 15	...	0 15
3920 5	C II	4	0 27	0 37	0 29
3918 8	C II	4	0 16		0 16
3889 0†	H8	2			11 6
3888 6†	He I	2			
3871 8	He I	60	0 11	0 38	0 20
3868 7	[Ne III]	1F	2 45	4 6	2 99
3867 6	He I	20	0 10		0 10
3862 6	Si II	1	0 06		0 06
3856 1	N II ?	30	0 14		0 14
3850 4	Mg II	5	0 04		0 04
3848 2	Mg II	5	0 07		0 07

* Line of stellar origin.
† Intensity from O'Dell (1963)

TABLE 2—*Continued*

λ	Ident	Mult	*I* (Ring)	*I* (Strip)	*I*
3838 6	Mg I	3	0 07	.	0 07
3835 4	H9	2	4 54	6 8	5 30
3833 6	He I	62	0 09	. . .	0 09
3819 6	He I	22	1 22	1 33	1 25
3805 8	He I	62	0 10	. .	0 10
3797 9	H10	2	3 88	5 0	4 25
3770 6	H11	2	3 62	4 3	3 85
3750 1	H12	2	3 04	3 49	3 16
3734 4.	H13	3	2 72	2 67	2 70
3728 9†	[O II]	1F	..	.. ..	147
3726 2†	[O II]	1F			
3723 9	....	. ..	0 21	. ..	0.21
3721 9	H14	3	2 78	2 60	2 72
3712 0	H15	3	2 10	2 05	2 09
3705 1	He I	25	0 85	0 70	0 80
3705 0	He I	25			
3703 9	H16	3	1 81	1 69	1 77
3697 1	H17	3	1 57	1 70	1 61
3691 6	H18	4	1 44	1 80	1 63
3686 8	H19	4	1 27	1 08	1 22
3682 8	H20	4	1 13	1 06	1 12
3679 4	H21	4	1 21	1 00	1 06
3676 4	H22	4	0 86	0 70	0 82
3673 8	H23	5	0 78	0 78	0 78
3671 5	H24	5	0 77	0 60	0 71
3669 5	H25	5	0.70	0 76	0 72
3667 7	H26	5	0 66	0 57	0 63
3666 1	H27	5	0 64	0 80	0 69
3664 7	H28	6	0 52	.	0 52
3663 4	H29	6	0 50	.	0 50
3662 3	H30	6	0 45		0 45
3661 2	H31	6	0 36	.	0 36
3660 3	H32	6	0 38	..	0 38
3659 4	H33	6	0 31	.. ..	0 31
3658 6	H34	7	0 41	.. .	0 41
3634 4	He I	28	0 65	.	0 65
3613 6	He I	6	0 86	. .	0 86
3587 3	He I	31	0 50	.	0 50
3554 5	He I	34	0 44	.. ..	0 44
3530 5	He I	36	0 39	. .	0 39
3512 5	He I	38	0 22		0 22
3447 5	He I	7	0 59		0 59
3354 6	He I	8	0 26		0 26
3187 7	He I	3	3 2		3 2

III. DISCUSSION

Except for the weakest lines, we estimate that most of the intensities are accurate to better than 20 per cent. Now H9, λ 3835, which is virtually burned out on some of the plates, shows a substantial scatter, but since all the other hydrogen lines show good agreement among themselves, we can regard this as an accidental error.

There are, however, a number of substantial differences between the "ring" intensities and the "strip" intensities (fourth and fifth columns). We normalized the two systems with all the lines; hence all ions with the same spatial distribution of their emissions give similar intensities in the two columns. On the other hand, those ions which show substantially different spatial distributions will give different results. Thus, [Ne III] λ 3868 is about twice as strong on EC 2439 as on the plates exposed on the ring. Similarly [S II] λ 4068 is concentrated in the ring where it is stronger than λ 4026 He I, while the opposite is true for plate 2439 centered on the central star. The green nebular lines show a spatial distribution similar to that of λ 3868, but they were too strong to measure by photographic methods.

Some kind of an average of the "strip" and "ring" intensities would simulate the intensities measured in the integrated light of the nebulae as measured photoelectrically. This fact must be taken into account in using P.E.P. intensities to calibrate slit spectra that refer only to a portion of the nebula.

Thus, the last column of Table 2 gives the finally adopted intensities for IC 418 which are intended to represent sort of a mean taken over the entire nebula, although in detailed applications stratification effects must be considered.

TABLE 3

THE EMISSION SPECTRUM OF THE CENTRAL STAR

λ	Ident.	I*	I (1954)*
4686 . .	He II	0 41	0 41
4658 6	C IV	31	. .
4651 4	C III }	54	{ 21
4650 2	C III }		38
4647 4	C III	.70	57
4643 1	N II	26	
4641 9	N III }	75	43
4640 6	N III }		
4634 2	N III	.37	25
4325 7	C III	14	0 19
4116 1	Si IV	45	
4088 9	Si IV	0 39	

* The third column gives peak intensities measured in the present study, while the fourth column gives the values found by Aller and Wilson (1954), which are expressed in equivalent angstroms of the underlying continuum, multiplied by the value of the continuum corrected to outside the atmosphere

In addition to the usual low-excitation forbidden lines [N II], [O II], [O III], [Ne III] and [S III], the spectrum of IC 418 includes the recombination lines of C II, N II (?), O II, and probably Mg II. The Mg I λ 4571 line is probably excited by collisions. Note particularly that the Balmer lines of hydrogen are followed to H34. The lines are sufficiently narrow so that the intensities to H33 at λ 3659 are probably reliable. The intensities of lines shortward of λ 3563 are not very accurate.

We present plates EC 2438 and EC 2439 in Figure 1. The upper spectrum of each strip is that of the central star plus nebula (EC 2439), and the lower that of the nebula only (EC 2438). Note the broad, hazy emission lines at about λ 4650 produced in the central star. Several stellar absorption lines are visible, particularly those of He II, and one can just make out the absorption lines underlying the hydrogen emission lines in the upper spectrum. The interstellar calcium "K"-line is also visible.

IV. REMARKS CONCERNING THE SPECTRUM OF THE CENTRAL STAR

Plate EC 2439 records the spectrum of the central star upon which is superposed that of the nebula. It is easy to separate the stellar and nebular lines; the former are considerably broader and show a higher excitation. Further, the plates are taken in such a way that the nebula was trailed the entire length of the slit, but the star filled only the central half of the field.

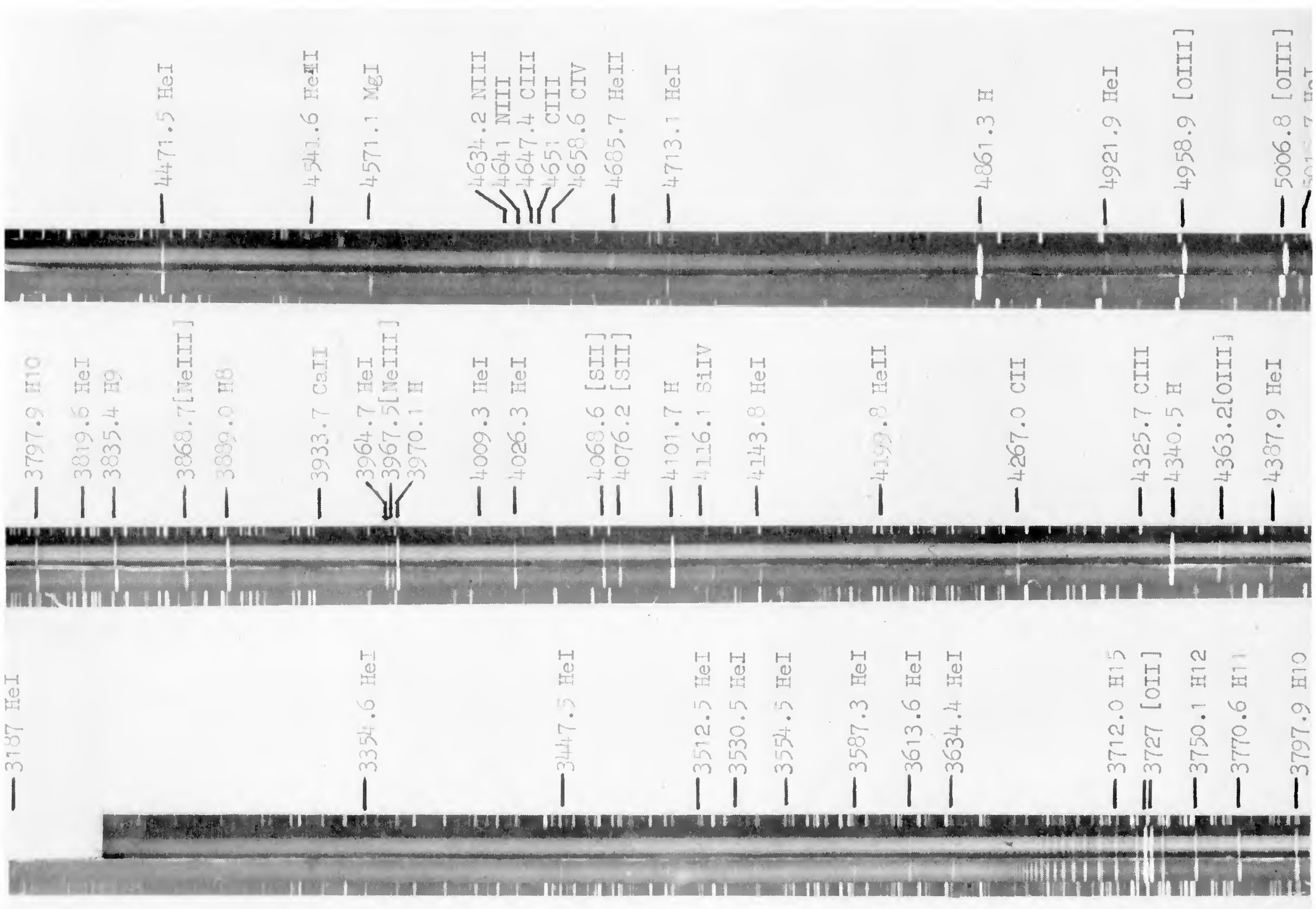

FIG. 1.—The spectrum of IC 418. The upper spectrum of each strip is that of the nebula plus central star, while the lower ıat of the nebula only.

The peak intensities of the emission lines were measured here. The absorption spectrum of the central star will be treated in a later paper. It is interesting to compare the stellar emission lines with those measured earlier by Aller and Wilson (1954), who gave the emission-line intensities in equivalent angstroms of the underlying continuum. This value multiplied by the intensity of the continuum gives the "area" of the emission line which is roughly proportional to the peak intensity corrected for plate sensitivity, atmospheric extinction, etc. Since Aller and Wilson gave no data on the continuum itself, we measured it on the plate EC 2439 beneath each of their lines. The results are presented in Table 3 where the intensities derived from Aller and Wilson's data have been scaled down to fit the intensities measured in this study at λ 4686 of He II. The columns give wavelength, identification, present intensity, and reduced intensity from the 1954 study. Note that there may still be a scale-factor difference between the two sets of intensities.

Note the lines of C IV and Si IV added to the earlier work.

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