SPECTROPHOTOMETRIC STUDIES OF GASEOUS NEBULAE

VII. THE RING PLANETARY NGC 7662

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ABSTRACT

Long-exposure spectrograms of NGC 7662 secured with the 100- and 200-inch coudé spectrographs are supplemented by photoelectric observations obtained with the coudé scanner of the 100-inch and other photoelectric measurements to obtain line identifications and intensities from λ 3121 to λ 5047. Electron densities have been measured at several points in the nebulae from [O II] ratios The symmetrical, highly stratified structure of this nebula, together with the high excitation of its spectrum, makes it a particularly valuable object for theoretical studies, although it has a less rich spectrum than has NGC 7027

I. INTRODUCTION

The Ring Nebula in Andromeda, NGC 7662, is among the brightest and aesthetically most beautiful of planetaries. Since it is also well placed for observation in the northern hemisphere, has a fairly regular structure and a rich, high-excitation spectrum, it has been intensively studied. This double-ring planetary shows pronounced stratification; high-excitation lines are produced in the bright inner ring, low-excitation emissions originate predominantly in the faint outer shell.

Among the earliest spectrophotometric studies of NGC 7662 are those of Page (1936, 1942), who was concerned primarily with the nebular continuum. Spectrophotometric measurements secured with the Crossley reflector in 1938 and 1939 yielded integrated intensities of the strongest lines from λ 3000 to λ 5000 (Aller 1941). Bowen and Wyse (1939) and Wyse (1942) made very detailed studies of the spectrum from λ 3700 to λ 6700. They discovered many new lines, many of them belonging to heretofore unknown ions, and estimated intensities by eye with the aid of calibrated scale plates. Since they used an image slicer in front of the spectrograph slit, the intensities are averages over the disk. At Mount Wilson Observatory, Minkowski and Aller (1956) measured line intensities from λ 3700 to λ 8200 at five points in the nebula. By using a guide star it was possible to make accurate positional settings in the nebula. Laboratory photometric calibrations plus a comparison star permitted relative line intensities to be measured over long spectral ranges. These data later served for abundance calculations (Aller 1957) by the methods of Bowen and Wyse (1939) and Menzel and Aller (1945).

By photoelectric photometry with an objective prism and the Curtis Schmidt telescope, Liller and Aller (1954) measured the intensities of λ 4959 and λ 5007 of [O III] and Hβ, from which they derived an electron density of 6300 cm^{-3} and (with the aid of photographically determined λ 4363 intensity) an electron temperature of $T_e = 15000°$ K. In 1956, Liller and Aller (1963) made measurements with a photoelectric spectrophotometer at the Newtonian foci of the 100-inch reflector. Later O'Dell (1963) made similar measurements with a Cassegrain spectrophotometer at Mount Wilson.

O. C. Wilson (1950) made detailed measurements of the expansion velocities in NGC 7662, noting that the expansion velocities were largest for [O II] and least for [Ne V]. Isophotic contours of monochromatic images were first attempted by Berman (1930). Monochromatic nebular photographs secured by Wilson and Minkowski at Mount Wilson and Palomar yield more adequate isophotes (Aller 1956). They show that, although the nebula departs from elliptical symmetry, the assumption of such a symmetry is useful in a first approximation.

Kaler (in preparation) obtains $T_e = 12800°$ K from an average of the [O III] intensity measurements of several workers and an improved interstellar reddening constant.

II. THE OBSERVATIONS AND REDUCTIONS

Table 1 lists the plates used in this study in order of increasing effective exposure. In all cases, the central star was centered on the spectrograph slit, which was placed across the brightest portion of the nebula, so that we obtained a cross-section of the nebula. We are primarily interested in the very faint lines, so we traced the spectrum of the bright ring only. We traced Ce 14768 on the brightest side of the central star only, and all the others on both sides. In all cases, we used a wedge calibrating spectrograph to

TABLE 1

THE OBSERVATIONS

Plate	Telescope	Date	Exp (min)	Dispersion (Å/mm)	λ (Å)
Ce 14768	100-inch	Sept. 1, 1961	143	20	3132–4740
Ce 12106	100-inch	Aug. 23–24, 1958	712	20	3132–4725
Pe 1813	200-inch	Oct. 16, 1954	550	39	4350–5000
Pe 1816... .	200-inch	Oct. 18, 1954	520	39	3731–4391

provide standards. Where possible, the standards were traced every 300 or 400 Å or so to allow for the variation of the slope of the characteristic curve with wavelength, and all curves for a given plate fitted through a point at one-half full deflection. Unfortunately, the calibrating spectrographs used cannot supply standards shortward of λ 3800 Å, so that we were forced to use this curve for the entire ultraviolet. We discuss this problem further in § III. Since all the lines are of nearly the same width, we measured only peak deflections, which are proportional to the total energy radiated in the line.

After the correction of the microphotometer deflections for the characteristic curve of the plate, the major problem of intensities lies on the correction of the observations for such wavelength-dependent effects as plate sensitivity, transmission of the optics, and atmospheric extinction. The plates were exposed such that a large number of lines spaced throughout the spectrum can be accurately measured on a given plate and also on the one with the next longest exposure time. The first plate, Ce 14768, was corrected to outside the atmosphere by making use of the photoelectric measurements of the stronger lines secured by Liller and Aller (1963), which cover the region λλ 3340–5007, and new observations with the 100-inch coudé which cover the region λλ 3132–3444, plus λ 4340. These intensities have been corrected to outside the atmosphere by standard star observations, and are presented in Table 2, together with two additional points taken from Chopinet (1963). Ce 14768 was of short enough exposure to record accurately many of the fainter lines measured photoelectrically. A comparison of line intensities thus gives us a correction-curve for all the above-mentioned effects at once. We then use the corrected intensities of Ce 14758 to obtain a correction-curve for Ce 12106, and then apply these results to Pe 1813–1816. In this way the faintest lines measured on the Palomar plates [$\sim$0.0002 $I(H\beta)$] can be tied into Hβ.

We chose the Liller and Aller (plus 100-inch coudé) photoelectric intensities for the correction, as they appeared to give the most self-consistent correction-curve for Ce 14768, with the least amount of scatter, and no observed systematic intensity effects.

In addition to the photometric measurements, the plates of effectively longest exposure, Pe 1813–1816, and portions of Ce 12106 were measured with a comparator for purposes of line identification. We measured for wavelength a number of lines which

TABLE 2

THE PHOTOELECTRIC INTENSITIES

λ	*I* (Mt W Coudé)	*I* (Liller & Aller)
3133	78	
3203	31	
3340	9 0	24
3345	3 0	
3427	...	..
3444	15 1	19
3727		10
3797		7 1
3835		7 8
3868		66 3
3889		13 9
3970		34 9
4101		23 5
4340	45	43 6
4363		16 0
4471		3 7
4541		2 9
4634–50		5 9
4686		64 3
4712		10 6
4740		7 8
4861		100
4959		335
5007		990

were missed by this procedure directly from the tracing. A line was first identified as real by superimposing the two traces which correspond to opposite sides of the bright ring. If they appeared on both traces, we measured the wavelength and intensity.

Identifications for permitted lines were made from Moore's (1945) *Revised Multiplet Table*, while the work of Bowen (1955, 1960) served to identify the forbidden lines.

In a number of cases, lines were identified with the comparator that were not detectable on the tracing. These lines probably arise in regions of lower (or higher) excitation away from the bright ring, and were therefore not traced. These lines are included in the results given in Table 3.

III. THE RESULTS

The problem of intensities is complicated by the effect of stratification, which NGC 7662 exhibits to a marked degree. As usual, the excitation level of the nebula decreases as we proceed outward, the He II radiation coming from the center with the He I lines at the outer part of the bright ring, etc. An individual line can show a rapid change in

TABLE 3

THE SPECTRUM OF NGC 7662

λ	λ_{lab}	Ion	Transition	I
3121.69....	3121.7	O III	$3p\,^3S - 3d\,^3P_1$	1.84
3132.91....	3132.9	O III	$3p\,^3S - 3d\,^3P_2$	78
3187.74....	3187.7	He I	$2\,^3S - 4\,^3P$	1.21
3203.23....	3203.1	He II	$3\,^2D - 5\,^2F$	31
3241.72....	3241.7	[Na IV]	$^3P_2 - {}^1D$	0.56
3265.47....	3265.5	O III	$3p\,^3D_3 - 3d\,^3F_4$	....
3299.42....	3299.4	O III	$3s\,^3P_0 - 3p\,^3S$	4.7
3310*......	....	....	......	0.19
3312.35....	3312.3	O III	$3s\,^3P_1 - 3p\,^3S$	8.0
3340.85....	3340.7	O III	$3s\,^3P_2 - 3p\,^3S$	12.8
3342.68....	3342.5	[Ne III]	$^1D - {}^1S$	0.34
	3342.9	[Cl III]	$^4S - {}^2P_{3/2}$	....
3345.89....	3345.8	[Ne V]	$^3P_1 - {}^1D$	4.0
3362.21....	3362.2	[Na IV]	$^3P_1 - {}^1D$	0.23
3381.25....	3381.3	O IV	$3s\,^4P_{3/2} - 3d\,^4D_{5/2}$	0.18
3385.53....	3385.6	O IV	$3s\,^4P_{5/2} - 3d\,^4D_{7/2}$	0.16
	3396.8	O IV	$3s\,^4P_{3/2} - 3d\,^4D_{3/2}$	0.10
3403.52....	3403.6	O IV	$3p\,^2P_{1/2} - 3d\,^2D_{3/2}$	0.17
3405.81....	3405.7	O III	$3p\,^3P_0 - 3d\,^3P_1$	0.38
	3407.4	O II	$3p'\,^2D - 4s'\,^2D$	0.11
3411.84....	3411.8	O IV	$3p\,^2P_{3/2} - 3d\,^2D_{5/2}$	0.32
3415.19....	3415.3	O III	$3p\,^3P_1 - 3d\,^3P_1$	0.44
3425.94....	3425.9	[Ne V]	$^3P_2 - {}^1D$	9.25
3428.69....	3428.7	O III	$3p\,^3P_1 - 3d\,^3P_2$	3.88
3430.51....	3430.6	O III	$3p\,^3P_2 - 3d\,^3P_1$	0.56
3433*......	....	....	......	0.23
3444.09....	3444.1	O III	$3p\,^3P_2 - 3d\,^3P_2$	17.2
	3447.6	He I	$2\,^1S - 6\,^1P$	0.11
	3512.5	He I	$2\,^3P - 12\,^3D$	0.12
	3530.5	He I	$2\,^3P - 11\,^3D$	0.08
	3554.4	He I	$2\,^3P - 10\,^3D$	0.13

TABLE 3 -continued

λ	λ_{lab}	Ion	Transition	I
3569*......	....	....	......	0.15
	3587.3	He I	$2\,^3P - 9\,^3D$	0.28
3606*......	....	....	......	0.14
	3613.6	He I	$2\,^1S - 5\,^1P$	0.26
	3634.2	He I	$2\,^3P - 8\,^3D$	0.37
	3661.2	H 31	$2\,^2P - 31\,^2D$	0.27
	3662.3	H 30	$2\,^2P - 30\,^2D$	0.31
	3663.4	H 29	$2\,^2P - 29\,^2D$	0.39
	3664.7	H 28	$2\,^2P - 28\,^2D$	0.37
	3666.1	H 27	$2\,^2P - 27\,^2D$	0.38
	3667.7	H 26	$2\,^2P - 26\,^2D$	0.43
	3669.5	H 25	$2\,^2P - 25\,^2D$	0.39
	3671.5	H 24	$2\,^2P - 24\,^2D$	0.49
	3673.8	H 23	$2\,^2P - 23\,^2D$	0.53
	3676.4	H 22	$2\,^2P - 22\,^2D$	0.68
	3679.4	H 21	$2\,^2P - 21\,^2D$	0.72
	3682.8	H 20	$2\,^2P - 20\,^2D$	0.86
	3686.8	H 19	$2\,^2P - 19\,^2D$	0.94
	3690.0	He II	$4\,^2F - 36\,^2G$	0.14
	3691.6	H 18	$2\,^2P - 18\,^2D$	1.28
	3695.6	He II	$4\,^2F - 34\,^2G$	0.21
	3697.2	H 17	$2\,^2P - 17\,^2D$	1.49
	3698.7	He II	$4\,^2F - 33\,^2G$	0.21
	3702.3	He II	$4\,^2F - 32\,^2G$	†
	3703.9	H 16	$2\,^2P - 16\,^2D$	1.72
	3705.0	He I	$2\,^3P - 7\,^3D$	0.38
	3707.2	O III	$3p\,^3P_1 - 3d\,^3D_2$	0.36
	3709.5	O III	$3s\,^5P_1 - 3p\,^5D_0$	†
	3710.4	He II	$4\,^2F - 30\,^2G$	0.12
	3712.0	H 15	$2\,^2P - 15\,^2D$	2.10
	3715.0	He II	$4\,^2F - 29\,^2G$	0.48
	3715.1	O III	$3p\,^3P_2 - 3d\,^3D_3$	
	3720.4	He II	$4\,^2F - 28\,^2G$	0.19

TABLE 3 -continued

λ	λlab	Ion	Transition	I
3721.98....	3721.94	H 14	$2^2P - 14^2D$	3.08
	3721.7	[S III]	$^3P_1 - {}^1S$	
3726.13....	3726.05	[O II]	$^4S - {}^2D_{3/2}$	6.0
3728.84....	3728.80	[O II]	$^4S - {}^2D_{5/2}$	3.38
3731.6*....	3732.1	O III	$3p\,^3P_2 - 3d\,^3D_1$	0.41
3732.75....	3732.8	He II	$4^2F - 26^2G$	0.22
3734.40....	3734.37	H 13	$3^2P - 13^2D$	3.1
3736.70....	3736.78	O IV	$3d\,^4D_{7/2} - 3d\,^4F_{9/2}$	0.11
3740.25....	3740.1	He II	$4^2F - 25^2G$	0.13
3748.75....	3748.6	He II	$4^2F - 24^2G$	0.15
3750.19....	3750.15	H 12	$2^2P - 12^2D$	3.5
3754.69....	3754.67	O III	$3s\,^3P_1 - 3p\,^3D_2$	1.57
3757.29....	3757.21	O III	$3s\,^3P_0 - 3p\,^3D_1$	0.68
3759.87....	3759.87	O III	$3s\,^3P_2 - 3p\,^3D_3$	5.60 ‡
3761.67....	....	....	......	0.04
3769.01....	3769.0	He II	$4^2F - 22^2G$	0.23
3770.61....	3770.63	H 11	$2^2P - 11^2D$	4.4
3773.90....	3774.00	O III	$3s\,^3P_1 - 3p\,^3D_1$	0.34
3776.93....	3777.16	Ne II	$3s\,^4P_{1/2} - 3p\,^4P_{3/2}$	0.07
3779.6*....	....	....	......	0.05
3781.70....	3781.68	He II	$4^2F - 21^2G$	0.24
3783.77....	3783.56	[Fe V]	$^5D_2 - {}^3F_3$	0.08 ‡
3784.94....	3784.89	He I	$2^1P - 12^1D$	0.05
3791.28....	3791.26	O III	$3s\,^3P_2 - 3p\,^3D_2$	0.51
3796.38....	3796.33	He II	$4^2F - 20^2G$	0.23
3797.91....	3797.90	H 10	$2^2P - 10^2D$	6.7
3806.21....	3805.77	He I	$2^1P - 11^1D$	0.07
3810.8*....	3811.0	O III	$3s\,^3P_2 - 3p\,^3D_1$	0.05
3813.43....	3813.50	He II	$4^2F - 19^2G$	0.46
3819.65....	3819.61	He I	$2^3P - 6^3D$	0.74
3833.74....	3833.80	He II	$4^2F - 18^2G$	0.59
3835.40....	3835.39	H 9	$2^2P - 9^2D$	8.0
3839.8*....	3839.52	[Fe V]	$^5D_3 - {}^3F_3$	0.05

TABLE 3 -continued

λ	λ_{lab}	Ion	Transition	I
3858.12....	3858.07	He II	$4^2F - 17^2G$	0.58
3862.42....	3862.59	Si II	$3p^2\ ^2D_{3/2} - 4^2P_{1/2}$	0.06
3868.70....	3868.76	[Ne III]	$^3P_2 - ^1D$	66.3
3875.5*....	3875.8	O II	$3p\ ^4D_{7/2} - 3d\ ^2F_{5/2}$	0.06
3887*......	3887.44	He II	$4^2F - 16^2G$	14.1
3888.79....	3888.65	He I	$2\ ^3S - 3\ ^3P$	
3889.......	3889.05	H 8	$2^2P - 8^2D$	
3891.20....	3891.28	[Fe V]	$^5D_4 - ^3F_4$	0.09 §
3894.9*....	3895.52	[Fe V]	$^5D_3 - ^3P_2$	0.04
3918.6*....	3918.98	C II	$3\ ^2P_{1/2} - 4^2S$	0.04
3920.79....	3920.68	C II	$3\ ^2P_{3/2} - 4^2S$	0.05
3923.43....	3923.48	He II	$4^2F - 15\ ^2G$	0.94
3926.56....	3926.53	He I	$2\ ^1P - 8^1D$	0.06
3932.3*....	....	....	......	0.08 ‡
3934.54....	....	....	......	0.06
3944.2*....	....	....	......	0.03
3948.08....	....	....	......	0.05
3956.81....	....	....	......	0.03
3965.04....	3964.73	He I	$2\ ^1S - 4^1P$	0.39
3967.50....	3967.47	[Ne III]	$^3P_1 - ^1D$	19.2
3968*......	3968.43	He II	$2^2F - 14^2G$	†
3970.09....	3970.07	H 7	$2^2P - 7^2D$	14.6
3997.44....	3997.37	[F IV]	$^3P_1 - ^1D$	0.04
4003.54....	4003.64	N III	$4^2D_{5/2} - 5\ ^2F_{7/2}$	0.03
4008.1*....	4008.4	[Fe III]	$^5D_4 - ^3G_4$	0.03 §
4009.27....	4009.27	He I	$2\ ^1P - 7^1D$	0.12
4026.04....	4026.19	He I	$2\ ^3P - 5\ ^3D$	2.37
4041.5*....	4041.3	O II	$3d\ ^4F_{5/2} - 4f\ ^4F_{5/2}$	0.03
4047.8*....	4048.2	O II	$3d\ ^4F_{7/2} - 4f\ ^4F_{7/2}$	0.03 ‡
4057.0*....	....	....	......	0.03
4058.7*....	....	....	......	0.03
4060.18....	4060.22	[F IV]	$^3P_2 - ^1D$	0.13
4068.48....	4068.60	[S II]	$^4S - ^2P_{3/2}$	0.78
	4069.9	O II	$3p\ ^4D_{3/2} - 3d\ ^4F_{5/2}$	....

TABLE 3 -continued

λ	λlab	Ion	Transition	I
4070.26....	4070.30	C III	$4\,^3F_4 - 5\,^3G_5$	0.82
4072.08....	4072.16	O II	$3p\,^4D_{5/2} - 3d\,^2F_{7/2}$	0.19
4076.10....	4076.35	[S II]	$^4S - ^2P_{1/2}$	0.21
4078.67....	4078.86	O II	$3p\,^4D_{3/2} - 3p\,^4F_{3/2}$	0.03
4081.6*....	4081.1	O III	$3s\,^3P_2 - 3p\,^3D_3$	0.03
4084.71....	4085.12	O II	$3p\,^4D_{5/2} - 3d\,^4F_{5/2}$	0.05
4087.15....	4087.16	O II	$3d\,^4F_{3/2} - 4f\,^4G_{5/2}$	0.04 §
4089.23....	4089.30	O II	$3d\,^4F_{9/2} - 4f\,^4G_{11/2}$	0.11
4092.8*....	4092.94	O II	$3p\,^4D_{7/2} - 3d\,^4F_{7/2}$	0.03
4097.39....	4097.31	N III	$3\,^2S - 3\,^2P_{3/2}$	2.75
4100.10....	4100.04	He II	$4\,^2F - 12\,^2G$	†
4101.73....	4101.74	Hδ	$2\,^2P - 6\,^2D$	20.0
4103.37....	4103.37	N III	$3\,^2S - 3\,^2P_{1/2}$	1.42
4107.18....	4107.07	O II	$3d\,^4F - 4f\,^4D$	0.03
4115.83....	4116.10	Si IV	$4\,^2S - 4\,^2P_{1/2}$	0.02
4117.60 ‖ ..	....	....	......	....
4119.16....	4119.22	O II	$3p\,^4P_{5/2} - 3d\,^4D_{7/2}$	0.08
4120.86....	4120.81	He I	$2\,^3P - 5\,^3S$	0.17
4122*......	4122.63	[K V]	$^4S - ^2D_{5/2}$	0.04
4128.67....	....	....	......	0.09
4131.6*....	....	....	......	0.03
4143.76....	4143.76	He I	$2\,^1P - 6\,^1D$	0.27
4146.06....	4146.09	O II	$3p\,^6P_{7/2} - 3d\,^6D_{9/2}$	0.03
4153.31....	4153.30	O II	$3p\,^4P_{3/2} - 3d\,^4P_{5/2}$	0.04
	4152.43	C III	$3p\,^3D_1 - 5\,^3F_2$	
4156.45....	4156.54	O II	$3p\,^4P_{5/2} - 3d\,^4P_{3/2}$	0.07
	4156.50	C III	$3p\,^3D_2 - 5\,^3F_3$	
4161.1*....	....	....	......	0.03 §
4163.05	4163.30	[K V]	$^4S - ^2D_{3/2}$	0.16 ‡
4166.6*....	....	....	......	0.07 §
4169.13....	4168.97	He I	$2\,^1P - 6\,^1S$	0.11
4171.62....	....	....	......	0.06 §

TABLE 3-continued

λ	λ_{lab}	Ion	Transition	I
4175.27....	....	....	......	0.05
4179.30....	....	....	......	0.11 §
4181.57....	4080.87	[Fe V]	$^5D_1 - {}^3P_0$	0.16
4186.94....	4187.05	C III	$4^1F - 5^1G$	0.50
4189.93....	4189.79	O II	$3p\,^2F_{7/2} - 3d\,^2G_{9/2}$	0.05
4195.59....	4195.70	N III	$3s\,^2P_{1/2} - 3p\,^2D_{3/2}$	0.03
4199.87....	4199.83	He II	$4^2F - 11^2G$	1.94
4227.60....	....	[Fe V]	$^5D_4 - {}^3H_4$	0.23
4237.42....	....	....	......	0.03
4251.4*....	....	....	......	0.03
4254.3*....	....	....	......	0.05
4258.0*....	....	....	......	0.05
4267.11....	4267.02	C II	$3\,^2D_{3/2} - 4\,^2F_{5/2}$	0.71
	4267.27	C II	$3\,^2D_{5/2} - 4\,^2F_{7/2}$	
4271.3*....	....	....	......	0.07
4273.9*....	....	....	......	0.11
4275.95....	4275.52	O II	$3d\,^4D_{7/2} - 4f\,^4F_{9/2}$	0.15
4295.24....	4294.82	O II	$3d\,^4P_{3/2} - 4f\,^4D_{5/2}$	0.04
4303.83....	4303.82	O II	$3d\,^4P_{5/2} - 4f\,^4D_{7/2}$	0.04
4316*......	....	....	......	0.05
4325*......	....	....	......	0.07
4338.97....	4338.67	He II	$4^2F - 10^2G$	†
4340.49....	4340.47	Hγ	$2^2P - 5^2D$	44.3
4349.73....	4349.93	O II	$3s\,^4P_{5/2} - 3p\,^4P_{5/2}$	†
4363.26....	4363.21	[O III]	$^1D - {}^1S$	16.0
4365.44....	....	....	......	†
4366.84....	4466.90	O II	$3s\,^4P_{5/2} - 3p\,^4P_{3/2}$	†
4368.58....	4368.30	O I	$3^3S - 4^3P$	†
4376.07....	....	....	......	0.10 ‡
4379.31....	4379.09	N III	$4^2F - 5^2G$	0.18
4387.97....	4387.93	He I	$2^1D - 5^1D$	0.41
4391.3*....	....	....	......	0.04
4407.4*....	....	....	......	0.09 ‡

TABLE 3 -continued

λ	λlab	Ion	Transition	I
4414.2*....	4414.4	O II	$3s\,^2P_{3/2} - 3p\,^2D_{5/2}$	0.14
4420.1*....	....	....	......	0.06
4434.49....	....	....	......	0.08
4437.52....	4437.55	He I	$2\,^1P - 5\,^1S$	0.11
4438.7*....	....	....	......	0.06
4447.99....	4448.21	O II	$3p\,^2F_{7/2} - 3d\,^2F_{7/2}$	0.12
4452.73....	4452.38	O II	$3s\,^2P_{3/2} - 3p\,^2D_{3/2}$	0.17
4458.62....	....	....	......	0.10
4471.50....	4471.48	He I	$2\,^3P - 4\,^3D$	3.2
4491.6*....	....	....	......	0.09
4510.97....	4510.93	[K IV]	$^1D - ^1S$	0.19
4535.0*....	4535.11	N III	$3p\,^4S_{3/2} - 3d\,^4P_{3/2}$	0.08
4541.52....	4541.59	He II	$4\,^2F - 9\,^2G$	3.5
4562.63....	....	....	......	0.09
4568.5*....	4568	O IV ?	$5\,^2F - 6\,^2D$	0.05
4571.14....	4571.10	Mg I	$3\,^1S - 3\,^3P_1$	#
4592.0*....	....	....	......	0.08
4597.1*....	....	....	......	0.08
4607.3*....	....	....	......	0.06
4610.9*....	....	....	......	0.11
4620.1*....	4618.8	C II	$3d\,^2F - 4f\,^2G$	0.05
4626.9*....	....	....	......	0.07
4632.8*....	....	....	......	0.27
4634.18....	4634.16	N III	$3\,^2P_{1/2} - 3\,^2D_{3/2}$	2.7
4640.59....	4640.64	N III	$3\,^2P_{3/2} - 3\,^2D_{3/2}$	4.0
4641.87....	4641.90	N III	$3\,^2P_{3/2} - 3\,^2D_{5/2}$	
4647.34....	4647.40	C III	$3\,^3S - 3\,^3P_2$	0.82
4648.67....	4649.14	O II	$3s\,^4P_{5/2} - 3p\,^4D_{7/2}$	† ‡
4650.29....	4650.16	C III	$3\,^3S - 3\,^3P_1$	0.47 ‡
4657.82 ‖ ..	4658.10	[Fe III]	$^5D_4 - ^3F_4$	....
4658.55....	4658.64	C IV	$5\,^2G - 6\,^2H$	0.75
4661.67....	4661.64	O II	$3s\,^4P_{3/2} - 3p\,^4D_{3/2}$	0.15
4683*......	....	....	......	1.03

TABLE 3 -continued

λ	λ_{lab}	Ion	Transition	I
4685.72....	4685.68	He II	$3^2D - 4^2F$	64.3
4711.40....	4711.34	[A IV]	$^4S - {}^2D_{5/2}$	8.8
4712.86....	4713.14	He I	$2^3P - 4^3S$	....
4714.11....	4714.25	[Ne IV]	$^2D_{5/2} - {}^2P_{3/2}$	0.75
4715.73....	4715.61	[Ne IV]	$^2D_{5/2} - {}^2P_{1/2}$	0.08
4724.08....	4724.15	[Ne IV]	$^2D_{3/2} - {}^2P_{3/2}$	0.73
4725.51....	4725.62	[Ne IV]	$^2D_{3/2} - {}^2P_{1/2}$	0.41 ‡
4740.22....	4740.20	[A IV]	$^4S - {}^4P_{3/2}$	8.4
4861.......	....	Hβ	$2^2D - 4^2D$	100.00
4883.9*....	....	....	......	0.15
4886.4*....	....	....	......	0.12
4906.6*....	4906.9	O II	$3p\,{}^4S_{3/2} - 3d\,{}^4P_{3/2}$	0.16
4922*......	4921.93	He I	$2^1P - 4^1D$	2.5
4931*......	4931.0	[O III]	$^3P_0 - {}^1D_2$	0.44
4959.......	4958.92	[O III]	$^3P_1 - {}^1D_2$	335
4999.3*....	....	....	......	2.6
5007.......	5006.85	[O III]	$^3P_2 - {}^1D_2$	990
5015.1*....	5015.7	He I	$2^1S - 3^1P$	10.8
5047*......	5047.7	He I	$2^1P - 4^1S$	2

* λ measured on trace.

† Line blended too severely for intensity measurement.

‡ Intensities agree poorly among tracings. Any number given is presented as an indication only.

§ Line is partially blended with another. This intensity probably represents an upper limit.

‖ Line not present on trace.

\# See text, section III.

intensity perpendicular to the dispersion. Also, lines of different ions will show variations at different distances from the central star, depending on the ionization potential. If the finite microphotometer slit is set so that one line will fully fill it, another will show intensity changes along the slit, with a consequent reduction in accuracy. Some lines will be missed entirely. In order to reach the faint lines, we had no choice but to set the slit on the bright ring. In order to minimize error we made the slit as short as possible, and were very careful to trace parallel to the dispersion so that different regions of the spectrum correspond to the same point in the nebula.

We have a similar problem, although less serious, in that we do not know whether the spectrograph slit was set on the same place in the nebula, or that each tracing was made at the same point in the nebula. In addition, we are correcting the line intensities of the bright ring with the photoelectric intensities that were obtained in the integrated light of the nebula.

Another difficulty enters with regard to the photometric calibration. The calibrating spectrograph was in all cases limited to wavelengths longer than λ 3800. Consequently the characteristic curve at about λ 3800 had to be used for the entire ultraviolet. This means that intensities of lines shortward of about λ 3500 will be affected by a systematic error. Every effort was made to minimize this effect for the faint lines. The intensities of these will probably be somewhat overestimated, while the strongest lines will be underestimated (except for those measured photoelectrically).

With the above in mind, we present the results in Table 3. The first column gives the wavelength as measured by comparator (corrected for the radial velocity of the nebula) or from the tracing itself, and the second, the standard wavelength as found in Moore's (1945) *Revised Multiplet Table* and Bowen's (1960) list of forbidden lines. The third column gives the probable identification and the fourth, the transition. The last column gives the adopted mean intensity, which, as was said before, corresponds to the bright ring. In determining the final intensity, we had to take into account the fact that while the Pe plates reached the faintest lines, the plates have the lowest resolution. Each line was examined individually on all plates to determine the best value to choose; e.g., the line should be unblended and on or near the straight part of the characteristic curve. Where the line is measurable to high accuracy on two or more plates, the intensities were averaged. The photoelectric results are also included in the final intensity. In general, the intensity differences between plates (or between traces for a given plate) show a random scatter, so we are justified in averaging, and in averaging the two traces of a given plate before correction to outside the atmosphere. There are a number of exceptions to this rule, which are noted in Table 3. In many cases a line will appear on one side of the central star, but not on the other, or the difference in intensity will be very large. In these instances, a number is given in the last column, but should be viewed as an indication of the intensity only and should not be used for abundance determinations, etc.

Particular mention should be made of the Mg I λ 4571 line. The intensities derived from the various plates show enormous variation—I(Ce 14768) $\cong$ 1.65, I(Ce 12106) = 0.72, I(Pe 1813) = 0.17. This ion must be extraordinarily sensitive to position within the nebula.

Because of the stratification, intensities of lines from ions of different ionization potential might be systematically different from one another. This is really noticeable for only the He II lines, which are measured systematically too faint on the Pe plates. Any further effects appear to be masked by random error. The He II intensities in Table 3 nearly all come from Ce 12106, as more could be measured due to the higher resolution, and we wanted a homogeneous set of values. This plate also appears to exhibit a somewhat higher accuracy.

The ultimate accuracy is difficult to assess. Except for the lines noted in the table, the lines between λ 3500 and λ 5000 are probably good to ± 20 per cent of the true value with respect to Hβ. The very faint lines are, of course, affected by larger random error and the very strong lines by less. Relative intensities of the lines that are adjacent in the spectrum and that are comparable in intensity should certainly be more accurate than the above figure. Shortward of λ 3500, the intensities become increasingly less accurate because of an increasingly erroneous characteristic curve.

We observe the permitted spectra (probably due to recombination) of the following ions: H, He I, He II, C II, C III, C IV, N III, O I, O II, O III, O IV, Ne II, Mg I, Si II, Si IV. The Mg I λ 4571 line is probably excited by electron collisions. Forbidden lines of [O II], [O III], [F IV], [Ne III], [Ne IV], [Ne V], [Na IV], [S II], [S III], [Cl III], [Ar IV], [Ar V], [K IV], [K V], [Fe III], and [Fe V] are also observed. The fluorescent lines of O III and N III (Bowen 1935) due to the action of Lyman-α of He II are strongly present.

IV. THE ELECTRON DENSITY

Theoretical discussions are deferred to a later paper. Electron temperatures are usually estimated from the λ 4363/($N_1 + N_2$) ratio; mean electron densities may be estimated from the surface brightness of the nebula and its angular diameter if we know the distance. The fact that the [O II] λ 3729/3726 ratio depends on density (Aller, Ufford,

TABLE 4

[O II] RATIOS AND ELECTRON DENSITIES

Position		r*	N_e cm^{-3}
Center		0 66	2 6×10^3
Inner ring	above star	55	4 5×10^3
	below star	.61	3 4×10^3
Outer ring	above star	57	4 2×10^3
	below star	0 55	4 5×10^3

* $r = I(\lambda\ 3729)/I(\lambda\ 3726)$.

and Van Vleck 1949) enables us to calculate N_e in individual filaments using equations by Seaton and Osterbrock (1957). These lines were best exposed on plate Ce 14768; we made tracings at five points—across the center of the nebula (across the central star) and at two points in each of the rings. Table 4 gives the line ratios and electron densities computed by the formula of Seaton and Osterbrock (1957), assuming an electron temperature of 12700° K (Kaler, in preparation).

Note that the electron density appears to be slightly smaller in the inner regions, which might suggest an inner region of less density, but quantitative conclusions cannot be drawn since most of the [O II] radiation probably originates in an outer shell seen in projection against the central regions. Furthermore, the doublet ratio and, therefore, the density are about the same in the [O II] emitting regions of both inner bright and outer faint ring. Slitless spectrograms show the inner ring to be very faint in [O II] radiation; both rings show about the same intensity in the spectrograms. Presumably, the density defined by the [O II] ratio refers throughout to condensations within the outer shell.

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