SPECTROPHOTOMETRIC STUDIES OF GASEOUS NEBULAE
VI. THE NON-THERMAL RADIO-FREQUENCY SOURCE PLANETARY NGC 3242

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ABSTRACT

The double-ringed planetary nebula NGC 3242 has been recently shown to have a strong component of non-thermal radio-frequency radiation. A spectrophotometric study involving photoelectric and photographic methods has been undertaken to establish intensities in the region λλ 3130–5007. Determination of the electron density and temperature by methods involving forbidden lines yields $T_\epsilon \sim 11500°$ K and $N_\epsilon \sim 6 \times 10^3$ electrons/cm^3; the latter value is confirmed by surface-brightness measurements.

INTRODUCTION

Aesthetically, NGC 3242 [$\alpha = 10^h23^m5^s$ (1965); $\delta = -18°28'$ (1965)] is one of the most beautiful of planetary nebulae. The central star, of photographic magnitude 11.3 (Liller 1955), is surrounded by a double-ring structure of integrated magnitude 8.8. The inner, bright, somewhat elongated ring has major and minor diameters of 26″ and 16″ in position angle of 45°; the outer, rather faint, oval disk, 40″ × 35″, has small irregularities near its edges (Curtis 1918). Observations by Minkowski show this nebula to have an extremely interesting structure. Wilson (1950, 1958) has measured the internal motions. O'Dell (1962) obtains a distance of 1030 pc for NGC 3242. The corresponding radius is 0.092 pc. Adopting $T = 46000°$ K for the central star, O'Dell (1963) finds its absolute photographic magnitude to be +0.6; its absolute bolometric magnitude −2.3.

The most notable feature of NGC 3242 is that it is a non-thermal radio source (Menon and Terzian 1965) and, therefore, is almost unique among the brighter, more easily observable planetaries. Hence, this object is worthy of detailed spectroscopic study.

Measurements of spectrograms secured with the Crossley reflector in 1944–1945 yielded intensities of the stronger lines (Aller 1951, 1953). Liller (1955) measured the integrated brightness of the nebula in the green nebular lines with narrow band-pass filters. Collins, Daub, and O'Dell (1961) also have done photoelectric photometry on this object, while isophotic contours have been measured on plates secured by Minkowski with the 200-inch telescope (Aller 1956).[1] Condensations occur near the end of the axis in the bright inner ring. A steep intensity gradient is seen near the edge of the light ring. Neither shell is uniform.

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[1] Assuming log $S(H\beta) = -1.13$, an intensity level corresponding to log $I = 1.00$ (on the contours depicted on p. 253 of *Gaseous Nebulae*) is evaluated as 2.9×10^{-3} erg cm^{-2} sec^{-1} steradian^{-1}. If spherical symmetry is assumed and one attempts to derive the emission per unit volume, $E(r)$, from the intensity distribution across the image, $I(x)$, $E < 0$ near the center; thus spherical symmetry cannot exist.

THE OBSERVATIONS

The far southern declination of NGC 3242 makes it a difficult object for spectrophotometric work from the northern hemisphere. Hence, a photoelectric spectrophotometric calibration from a station in the southern hemisphere was highly desirable. Accordingly, in 1961, two of us (D. J. F. and L. H. A) secured a series of scans with the Michigan spectrum scanner designed by Liller (1957) which was attached to the 50-inch telescope at Mount Stromlo. The observational procedures employed are similar to those used for a study of a number of southern planetaries (Aller and Faulkner 1964). Since the Michigan scanner was designed for an f/5 system and had to be used in f/18 and f/12 systems (the 50-inch focal ratio was f/18, whereas that of the 26-inch was f/12),

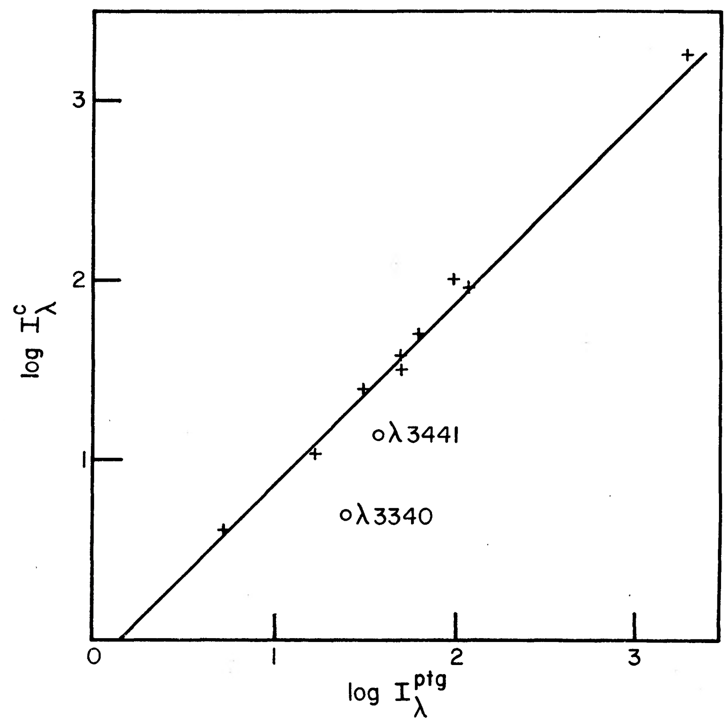

FIG. 1.—Plot of intensity measured photoelectrically versus that measured photographically

auxiliary optics had to be employed. Spectral resolutions ranging from 25 to 100 Å could be selected. At the lowest resolution one could observe the nebula in its integrated light. At the higher resolutions it was necessary to measure a strip in the bright ring.

Observations of selected standard stars falling near the equator, whose energy distributions had been measured by Code (1960), Oke (1960), and Rodgers (1961), and of southern stars, whose energy distributions had been measured in an independent program (Aller, Faulkner, and Norton 1964), provided the necessary data for calibration with regard to atmospheric extinction, transmission of optics, sensitivity of photocell, etc. Scans were secured on several nights, with different spectral resolutions and sensitivities in order to obtain the best data possible on line intensities, both in the bright ring and integrated over the nebula.

In Figure 1 we plot log I_λ^c versus log I_λ^{pg}, where I_λ^c is the intensity measured photoelectrically with "C" slots with a spectral resolution of 50 Å and I_λ^{pg} is the intensity measured photographically in 1944 with the quartz slitless spectrograph on the Crossley reflector (Aller 1951). Note the discordances for the ultraviolet lines which appear to have been measured as much too bright in the older photographic spectrophotometry necessarily carried out at large zenith distances.

Because of limited spectral resolutions (with available telescopes and photocell it was not possible to use a resolution smaller than about 25 Å), one must supplement photoelectric measurements by photographic spectrophotometry. Although the precision of a given measurement is less, high spectral resolution may be achieved, and weak lines may be recorded. It is necessary, however, to employ great care in the calibration. While the blackening–log I calibration presents no difficulty, the wavelength-dependent factor necessitates observing the spectrum of a suitable comparison star with the same apparatus. A final comparison of the photographic measurements for the stronger lines with the photoelectric measurements then supplies a final check on wavelength errors. Scale errors are more difficult to handle, since photoelectric measurements are not available for weaker lines; furthermore, scale errors may differ from one spectral region to another.

We pursued spectrophotometric measurements of NGC 3242 with the facilities made available to us at Mount Wilson (S. J. C. and L. H. A.) and Lick (L. H. A.) Observatories.

Successive columns of Table 1 give the plate number, date of observation, telescope and spectrograph, exposure time, and comparison star. Observations secured with the X-spectrograph and 8-inch camera on the 60-inch telescope at Mount Wilson ranged from 3 hours 40 min to 11 hours 10 min, the latter one being a 3-night exposure. These were supplemented by spectrograms secured with the 16-inch camera at the Mount Wilson coudé spectrograph and by spectra taken with the 20-inch camera at the 120-inch telescope coudé at Lick Observatory. The weakest lines were observed only with the f/1 air-Schmidt camera with the prime-focus spectrograph at the 120-inch.

For a comparison star, we used α Leonis with a calibrated quartz diffuser placed over the slit (Minkowski and Aller 1956). The central star of NGC 3242 served as a comparison star for the Lick coudé plate, while ϵ Orionis served as photometric standard for the prime-focus plates.

Table 2 summarizes the final results. Successive columns give the approximate wavelength, identification (based mostly on the *Revised Multiplet Table*), the intensity as measured with the photoelectric spectrophotometer (I_{pep}) (in Australia), the average of all photographic measurements secured with the 60-inch, the Mount Wilson coudé, and the Lick coudé telescopes ($\bar{I}_{pg}$), and in the fifth column the intensities measured with the Lick prime-focus spectrograph ($\bar{I}_{pf}$).

The lines of ions so far identified in the spectrum of NGC 3242 include H, He I, He II, C II, C III, C IV, N II, N III, O II, O III, O IV(?), [O II], [O III], [Ne III], [Ne IV], [Ne V], [Fe IV], Mg I, [Mg I], Mg II, [S II], [S III], [Ar II], [Ar IV], [Ar V], [K IV], [K V], [F III](?), and [Fe V]. The [N II] λλ 6548, 6584 lines, often prominent in the spectra of planetaries are absent in NGC 3242 on long exposures on Hα (White 1952). This is a high-excitation nebula, although by no means as highly excited as NGC 7662, NGC 2022, or NGC 4361.

If the agency responsible for the non-thermal radio-frequency emission from this nebula has any influence on the line spectrum, it is not immediately obvious. Indeed, we would not expect to find such effects among the stronger lines, but only perhaps among the weaker ones which are difficult to observe. Further observations will be required to settle this question.

INTERSTELLAR REDDENING

An estimate of the reddening correction needed for the nebula may be obtained from the observed Balmer decrement. Using the reddening law of Whitford (1958) and comparing the observed intensities of Hβ, Hγ, and Hδ with the 10000° K, "case B" values

TABLE 1

LIST OF OBSERVATIONS

Plate No.	Date of Observation	Telescope and Spectrograph	Exposure Time	Comparison Star	Remarks
X-7515	Mar. 6–7, 1963	60-inch (Mt. Wilson) X-spectrograph 8-inch camera	$5^h 30^m$	α Leonis	Quartz diffuser used with star
X-7518	Mar. 7–8, 1963	60-inch (Mt. Wilson) X-spectrograph 8-inch camera	3 40	α Leonis	Quartz diffuser used with star
X-7521	Mar. 8–11, 1963	60-inch (Mt. Wilson) X-spectrograph 8-inch camera	11 10	α Leonis	Quartz diffuser used with star
Ce 16760	Nov. 30–Dec. 1, 1963	100-inch (Mt. Wilson) coudé 16-inch camera	2 47	ξ_2 Ceti	Quartz diffuser used with star
Ce 16765	Dec. 1–2, 1963	100-inch (Mt. Wilson) coudé 16-inch camera	3 30	ξ_2 Ceti	Quartz diffuser used with star
B-2309	Feb. 9–10, 1964	60-inch (Mt. Wilson) B-spectrograph 3-inch Schmidt camera	2 30	α Leonis	5-mag. diaphragm used with star
Ce 17080	Apr. 25–26, 1964	100-inch (Mt. Wilson) coudé 16-inch camera	3 30	θ Crateris	
Ce 17084	Apr. 26–27, 1964	100-inch (Mt. Wilson) coudé 16-inch camera	1 15	θ Crateris	
Ec 1706	Jan. 5–6, 1963	120-inch (Lick) coudé 20-inch camera	4 0	Central star of nebula	
Ec 1709	Jan. 6–7, 1963	120-inch(Lick) coudé 20-inch camera	6 24	Central star of nebula	
Es 732	Feb. 4–5, 1964	120-inch (Lick) prime focus	2 0	ε Orionis	6.2-mag. diaphragm used with star
Es 740	Feb. 6–7, 1964	120-inch (Lick) prime focus	3 0	ε Orionis	6.2-mag. diaphragm used with star
Es 959	Feb. 7–8, 1965	120-inch (Lick) prime focus	3 0	ε Orionis	6.2-mag. diaphragm used with star

TABLE 2

NGC 3242: Compilation of Final Data

λ_{adopt}	Atom or Ion	Intensity*			
		I_{pep}	$\bar{I}_{pg}$	$\bar{I}_{pf}$	$\bar{I}_{adopt}$
3132.9	O III	...	...	2.3	2.3
3187.8	He I	...	...	3.3	3.3
3203.1	He II	...	...	8.3	8.3
3211	...	...	...	0.32	0.3
3218	O II*	...	...	0.30	0.3
3234	S III	...	...	0.36	0.4
3241.7	[Na IV]	...	...	0.27	0.3
3261.0	O III	...	...	0.36	0.4
3265.4	O III	...	...	0.37	0.4
3287	O II	...	...	0.24	0.2
3299.3	O III	...	...	5.5	5.5
3312.3	O III	...	...	...	...
3340.8	O III }	4.2	...	...	...
3345.9	[Ne V] }				
3355.0	He I, Ne II	...	...	0.24	0.2
3405.7	O III	...	...	0.27	0.3
3410	{O II, O IV}	...	...	0.19	0.2
3415.2	O III	...	...	0.56	0.6
3425.97	[Ne V] }	11.4	...	...	...
3444.0	O III }				
3530.6	He I	...	...	0.12	0.1
3554.3	He I	...	...	0.23	0.2
3568.5	Ne II	...	...	0.14	0.1
3574.3	Ne II	...	...	0.13	0.1
3587.3	He I	...	...	0.28	0.3
3591	C II	...	...	0.10	0.1
3600	...	...	...	0.08	0.08
3604	...	...	...	0.08	0.08
3613.6	He I	...	...	0.14	0.1
3619	...	...	...	0.05	0.05
3630	...	...	...	0.10	0.10
3634.2	He I	...	...	0.30	0.3
3671.5	H_{24}	...	...	0.46	0.46
3673.7	H_{23}	...	0.6	0.50	0.50
3676.3	H_{22}	...	...	0.52	0.52
3679.4	H_{21}	...	...	0.6	0.60
3682.8	H_{20}	...	0.6	0.65	0.65
3686.8	H_{19}	...	1.6	0.86	0.86
3691.5	H_{18}	...	0.90	0.96	0.93
3694.4	Ne II, He II	...	0.20	0.21	0.2
3697.2	H_{17}	...	1.3	1.18	1.2
3703.8	H_{16} }	...	2.7	1.6	2.2
3704.8	He I }				
3707.2	O III	...	...	0.32	0.3
3712.0	H_{15}	...	2.0	1.5	1.75
3715.1	O III	...	...	0.48	0.5
3721.9	H_{14}+[S III]	1.9	2.1	2.11	2.0
3726.0	[O II] }	9.0	{ 6.0	4.5	5.8
3728.7	[O II] }		{ 3.0	2.7	2.9
3732.8	He II	...	...	0.10	0.1
3734.3	H_{13}	1.7	1.7	2.4	2.0
3740.3	He II	...	...	0.05	0.05
3750.1	H_{12} }	4.9	{ 1.5	3.0	2.3
3754.6	O III }		{ 0.5	1.06	0.8
3757.3	O III }		{ 0.1	0.4	0.2
3759.9	O III }		{ 1.8	3.9	2.8
3770.6	H_{11} }		{ 1.8	3.65	2.7

* See text for explanation.

TABLE 2—*Continued*

λ_{adopt}	Atom or Ion	Intensity* I_{pep}	$\bar{I}_{pg}$	$\bar{I}_{pf}$	$\bar{I}_{adopt}$
3774.0	O III	...	...	0.27	0.3
3781.6	He II	...	...	0.14	0.1
3791.3	O III	...	...	0.31	0.3
3796.3	He II	...	...	0.14	0.1
3797.8	H_{10}	2.5	2.6	4.3	3.1
3805.8	He I	...	...	0.06	0.06
3813.5	He II	...	...	0.17	0.2
3819.7	He I	...	0.6	0.84	0.7
3827.0	Ar II ?	...	...	0.02	0.02
3833.8	He I, He II	...	...	0.21	0.2
3835.4	H_9	6.2	4.9	5.1	5.4
3839.6	[Fe V]	...	...	0.07	0.07
3851.1	[Fe V], O II	...	...	0.02	0.02
3858.0	He II	...	...	0.20	0.20
3866	...	...	...	0.11	0.11
3868.7	[Ne III]	77.0	68.0	...	73.0
3871.7	He I	...	...	0.10	0.1
3888.8	H_8, He I	13.3	13.5	...	13.4
3920.6	C II	...	...	0.08	0.08
3923.5	He II	...	...	0.24	0.2
3926.5	He I	...	...	0.07	0.07
3935.0	...	...	...	0.04	0.04
3944.9	O II	...	...	0.05	0.05
3948.0	C II	...	...	0.06	0.06
3964.8	He I	...	...	0.52	0.5
3967.5	[Ne III]	33.3	22.7	...	22.7
3970.1	H		10.7	...	10.7
4009.2	He I	...	...	0.15	0.15
4026.0	He I, He II	1.7	1.7	2.0	1.8
4041.4	O II, N II	...	...	0.03	0.03
4056.0	C III	...	...	0.02	0.02
4060.2	[F IV]	...	...	0.11	0.1
4068.6	[S II]	1.3	0.66	0.50	0.8
4072.1	O II		0.54	0.20	0.4
4076.2	[S II]	...	1.0 ?	0.19	0.2
4085.2	O II	...	...	0.07	0.06
4089.2	O II	...	...	0.13	0.13
4097.3	N III	24	1.4	1.60	1.5
4101.7	H_8		22.6	...	22.5
4112.5	O II	...	...	0.01	0.01
4120.8	He I	...	...	0.18	0.2
4143.8	He I	...	0.3	0.25	0.3
4153.3	O II	...	...	0.07	0.07
4156.3	O II, C III	...	...	0.03	0.03
4163.2	[K V]	...	...	0.02	0.02
4168.9	He I	...	...	0.05	0.05
4180.9	[Fe V]	...	...	0.04	0.04
4186.9	C III	...	0.3	0.23	0.2
4189.8	O II	...	...	0.05	0.05
4195.6	N III	...	...	0.03	0.03
4199.9	He II	...	0.8	0.58	0.7
4227.4	[Fe V]	...	0.4	0.13	0.2
4237.0	N II	...	...	0.03	0.03
4241.2	N II	...	...	0.06	0.06
4267.1	C II	...	0.8	0.74	0.8
4275.6, 4276.7	O II	...	...	0.08	0.08
4283.3	O II	...	...	0.03	0.03
4294.9	O II	...	...	0.05	0.05
4303.9	O II	...	...	0.07	0.07

* See text for explanation.

TABLE 2—*Continued*

λ_{adopt}	Atom or Ion	Intensity*			
		I_{pep}	$\bar{I}_{pg}$	$\bar{I}_{pf}$	$\bar{I}_{adopt}$
4313.95	O II	....	....	0.03	0.03
4317.2	O II	....	....	0.06	0.06
4325.8	O II	....	....	0.02	0.02
4331.4	O II	....	....	0.02	0.02
4340.4	Hγ	40.0	41	....	40.5
4349.4	O II	....	....	0.06	0.06
4363.2	[O III]	11.0	8.5	....	11.0
4379.2	N III	....	....	0.19	0.2
4387.9	He I	....	0.50	0.40	0.45
4391	Mg II?	....	....	0.04	0.04
4408	....	....	....	0.02	0.02
4414.9	O II	....	....	0.06	0.06
4431	Ne II	....	....	0.03	0.03
4437.5	He I	....	....	0.04	0.04
4453	....	....	....	0.02	0.02
4458	....	....	....	0.02	0.02
4471.4	He I	4.0	3.7	3.43	3.7
4481.2	Mg II	....	....	0.02	0.02
4511.0	[K IV]+N III	....	....	0.09	0.09
4517.0	C III	....	....	0.03	0.03
4523.6	N III	....	....	0.03	0.03
4534.6	N III	....	....	0.06	0.06
4541.5	He II	....	1.5	1.22	1.36
4562.5	[Mg I]	....	....	0.10	0.10
4570.9	Mg I	....	....	0.06	0.06
4611	[Ar V]	....	....	0.05	0.05
4620	C II, O II	....	....	0.02	0.02
4634.1	N III }	4.3	{ 1.8	....	1.8
4640.7	N III }		{ 2.7	....	2.6
4649.1	O II	....	2.0	0.48	0.5
4658	C IV	....	....	0.05	0.05
4661.6	O II	....	....	0.05	0.06
4669.2	....	....	....	0.03	0.03
4676.1	O II	....	....	0.06	0.06
4685.7	He II	31	36	....	32
4712	[Ar IV]+He I	5.3	5.1	....	5.2
4725.0	[Ne IV]	....	....	0.06	0.06
4740.1	[Ar IV]	5.0	4.9	....	5.0
4861	Hβ	100	95	....	100
4922.0	He I	....	....	0.32	0.3
4931.0	[O III]	....	....	0.05	0.05
4959.0	[O III]	420	346	....	420
5006.9	[O III]	1280	....	....	1280

* See text for explanation.

of Burgess (1958), we find that the best fit is obtained with a value for the interstellar extinction Hβ of

$$A(H\beta) = 1.3 \text{ mag.}$$

This correction seems large for an object of galactic latitude $b = +32°$; in fact, a combination of accidental errors in measuring the Balmer-line intensities could give a spurious value for the space extinction. The use of the 10000° K theoretical decrement will introduce little error, since the decrement is insensitive to electron temperature.

ELECTRON TEMPERATURE AND DENSITY

Theoretical interpretations of the spectrum of NGC 3242 will be deferred to a later paper when calculations of certain necessary parameters are complete (Czyzak and Krueger 1963).

Accepting an angular radius of 10″ for NGC 3242, Liller and Aller (1954) and Liller (1955) give $\log S(N_1 + N_2) = +0.10$, where $S(N_1 + N_2)$ is the flux in ergs cm^{-2} sec^{-1} at the outer boundary of the nebula in the light of the green nebular [O III] lines. Accepting $I(N_1 + N_2)/(H\beta) = 17$ on the basis of the present photoelectric measurements, $\log S(H\beta) = -1.13$. Correcting this for the interstellar extinction found in the previous section, we obtain $\log S(H\beta) = -0.61$. Now the flux in Hβ in ergs cm^{-2} sec^{-1} is related to the product of the ionic and electronic densities by

$$S(H\beta) = 7.60 \times 10^{-20} \frac{N_i N_\epsilon}{T_\epsilon^{3/2}} b_4(T_\epsilon) D e^{x_4} ,$$

where

$$x_4 = \frac{hRZ^2}{4kT_\epsilon} = \frac{9866}{T_\epsilon} \quad \text{and} \quad D \equiv 3d\left(1 - \frac{d}{A} + \frac{d^2}{3A^2}\right)$$

for a shell nebula. In the equation for D, the parameters d and A represent the thickness of the shell and the outer radius of the nebula, respectively. The parameter $b_4(T_\epsilon)$ is Menzel's (1961) b-factor which measures the departure of the population of the fourth level from that appropriate to thermodynamic equilibrium at a temperature T_ϵ. We have used the $b_4(T_\epsilon)$ values of Burgess (1958) since in his calculations the $nl \rightarrow nl'$ collisions are taken into account in a way which (as Pengelly and Seaton [1964] have shown) very well represents the physical conditions in planetary nebulae.

On the basis of Curtis' data, we chose $d/A = 0.2$ and $A'' = 9''.30$. Adopting O'Dell's estimate of the distance of NGC 3242 as 1030 pc, we find $D = 7.0 \times 10^{16}$ cm. If $T_\epsilon = 11500°$ K, we interpolate $\log b_4(T_\epsilon) = -0.62$ from the data of Burgess (1958). (A more accurate value of $\log b_4$ for the case B is being calculated by W. Clarke [private communication] but is not yet available.) Then, assuming $N_i = N_\epsilon$ we find $\log N_\epsilon = 4.0$ or $N_\epsilon = 1 \times 10^4$ electrons/cm^3, or 5.5×10^3 electrons/cm^3 if no space extinction is assumed.

The dependence of ratio of the intensities of the λ 3729 and λ 3726 lines of [O II] on the electron density (Aller, Ufford, and Van Vleck 1949) provides another means of estimating this quantity. Adopting equation (22) given by Seaton and Osterbrock (1957), and $r = I(\lambda\, 3729)/I(\lambda\, 3726) = 0.50$, we calculate $N_\epsilon = 6.28 \times 10^3$ electrons/cm^3 which suggests that filamentary effects are probably not important in the inner bright shell of NGC 3242. If one adopts $r = 0.72$ (Collins *et al.* 1961), he finds $N_\epsilon = 2 \times 10^3$ electrons/cm^3 which is somewhat smaller than our mean value. Possibly the λ 3727 radiation originates in the outer, more attenuated shell.

Finally, we may use the ratio of the λ 4363 and λ 4959 + λ 5007 lines of [O III] to determine the electron temperature. Using the collision strengths given by Seaton (1953, 1955, 1956, 1958) and the A-values of Garstang (1951) in the formula of Aller (1956), we find for the densities usually encountered in planetaries

$$T_\epsilon = 14300\left[\log \frac{I(N_1 + N_2)}{I(\lambda\, 4363)} - 0.85\right]^{-1} .$$

From Table 2, we find $I(N_1 + N_2)/I(\lambda\, 4363) = 154$, which becomes 127 when corrected for interstellar reddening. The corresponding electron temperature is $T_\epsilon = 11500°$ K.

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