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CHANGES IN THE PLANETARY NEBULA IC 4997

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Summary

Spectrophotometric measurements of the spectrum of the planetary nebula IC 4997 show that the λ4363 line of [O III] is currently decreasing in intensity relative to the λ4959, λ5007 forbidden lines of the same ion. The authors give evidence to support the idea that the spectral changes result from an expansion of the nebula with a corresponding decrease both in electron density and electron temperature.

1. *Introduction.* The planetary nebula IC 4997 'appears stellar on a 200 in. plate taken in good seeing' (Seaton & Osterbrock 1957), while according to Wilson & O'Dell (1962), 'the appearance of the nebula is elliptical in form, with a ratio of axes of about 0·7 and a major axis somewhat less than 2″·0. The nebula was first discovered by Mrs W. P. Fleming (Pickering 1896), and except for the unusual strength of the [O III] line at λ4363, the spectrum of this object is quite typical of planetary nebulae of medium excitation (Aller 1941). Only one other planetary nebula is known to exist with such an intense λ4363 radiation (Razmadze 1960), although this characteristic is typical of nova shells shortly after outburst. Menzel, Aller & Hebb (1941) interpreted this peculiarity as resulting from a high electron density in a small compact planetary. More recently, Seaton & Osterbrock (1957) arrived at the same interpretation through a study of the pair of [O II] lines at λ3727, but they were unable to evaluate the electron density because of the insensitivity of their method at high densities.

During the summer of 1956 Dr I. S. Bowen kindly made it possible for the writers to be guest investigators at the Mount Wilson Observatory. We were studying the spectra of gaseous nebulae, using the 100 in. telescope and a photoelectric spectrophotometer (Liller 1957). On the night of August 31, while observing the planetary IC 4997 for the first time, we discovered that the λ4363 line was weaker than Hγ at λ4340, a condition which had not been known to exist previously for this object‡.

The following section will summarize the past and present observations of IC 4997, including some that have not heretofore been published. A discussion of these observations will follow in the third section; some concluding remarks will appear in the last section.

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‡ In 1937 L. Berman suggested to one of us (LHA) that the ratio $I(\lambda 4363)/I(\lambda 4340)$ in IC 4997 might be variable, but an examination of then available data failed either to confirm or speak against this hypothesis.

2. *The observations.* A thorough search by Dr Martha H. Liller through the Harvard photographic plate collection revealed that the earliest existing spectral plates of IC 4997 were taken between 1887 and 1895. Presumably one of these was the plate on which the nebula was discovered. From the Harvard and the Lick Observatory plate collections, we found some two dozen plates taken before 1938, all but one of which show λ4363 clearly stronger than the neighbouring λ4340 line of Hγ. However, on this one plate, taken in 1897, the images are badly underexposed and only a few photographic grains contribute to the result.

In 1938 and 1939, Aller (1941) and T. L. Page secured the first calibrated plates, which yielded intensity ratios $I(\lambda 4363)/I(\lambda 4340)$ of 1·60 and 1·41 (these and all other observed values of this ratio appear both in Table I and in Fig. 1 (*a*)).

TABLE I

Intensity ratios of lines in IC 4997

Year	$\frac{I(\lambda 4363)}{I(H\gamma)}$	Observer, reference
1938	1·60	Aller (1941)
1939	1·41	Page (1942), Aller & Liller
1949	1·00	White (1952)
1956	0·758	Liller & Aller (1963)
1959	0·70	Aller
1959	0·61	Savel'eva (Vorontsov-Velyaminov 1960)
1961	0·682	Aller & Kaler (1964)
1962	0·689	O'Dell (1963)

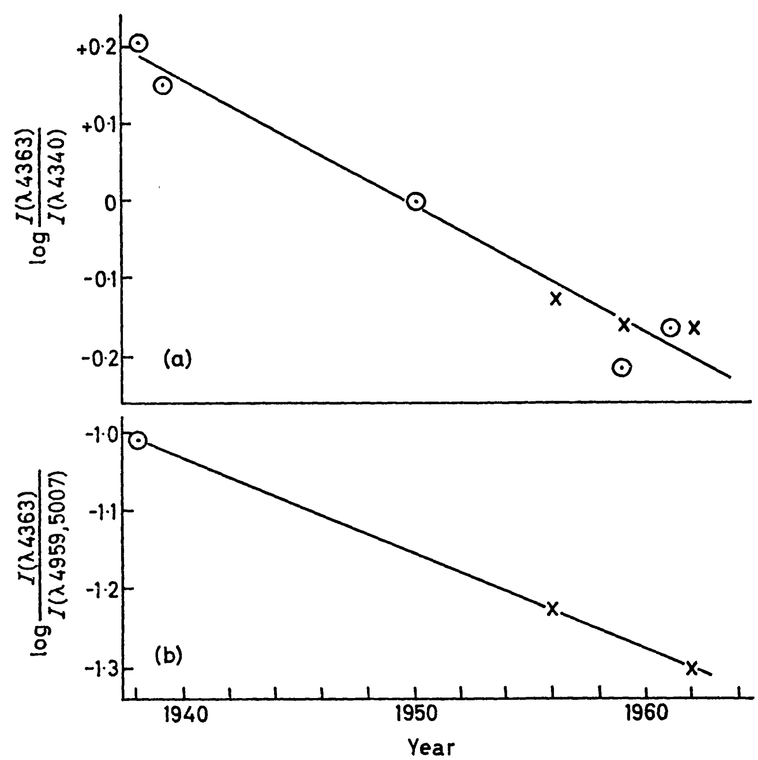

FIG. 1. *Spectral changes in IC 4997. (a) The logarithm of the ratio of intensities of λ4363 [O III] to Hγ; (b) the logarithm of the ratio of intensities of λ4363 [O III] to λ4959, λ5007 [O III].* ⊙, *photographic observation;* ×, *photoelectric observation. Corrected for interstellar reddening.*

Through the kindness of Dr B. Strömgren, the authors obtained the 1939 plates which were taken by Page (1942) for his work on the continuous spectra of planetary nebulae.

On a remarkable plate taken in Ann Arbor in 1949 by M. L. White (1952), the $\lambda 4363$ and $H\gamma$ lines appear of equal strength. Although the plate had no calibration, the nearness in wavelength of the two lines guarantees that the response characteristics of the plate were quite similar at the two wavelengths. We have therefore assumed that in 1949 the intensity ratio of the two lines was unity. One of us (L.H.A.), using the Mount Wilson 100 in. coudé scanner, obtained a value of 0·70 in 1959. Other recent precise values for $I(\lambda 4363)/I(\lambda 4340)$ have come from the photoelectric spectral scans made by O'Dell (1963) and by Liller & Aller (1963). Additional photographic points come from Savel'eva (see Vorontsov-Velyaminov 1960) and from Aller & Kaler (1964).

The particular choice of $H\gamma$ as a comparison line for $\lambda 4363$ was made for convenience only. Early uncalibrated plates can be compared meaningfully since response characteristics will change very little over the 23 Å separating the two lines. Using this line ratio to derive the physical conditions which exist in IC 4997 is risky, however, since the lines are produced by entirely different processes. It is far safer to compare $\lambda 4363$ with the green nebular lines of [O III] at $\lambda 4959$ and $\lambda 5007$. Other intensity ratios, such as $I(\lambda 3343)/I(\lambda 3869, \lambda 3967)$ of [Ne III], can provide independent means of deriving quantities such as the electron temperature and electron density.

When lines differ in wavelength by hundreds of Ångstroms, it becomes necessary to correct for the effects of interstellar absorption. From his measurements of the intensities of both Paschen and Balmer lines, O'Dell (1963) has derived accurate values for the amounts of interstellar reddening and absorption, and has compared the observed and theoretical ratios of the intensities of lines resulting from transitions from the same upper level. We will utilize his results throughout this paper.

TABLE II

Intensity ratios of lines in IC 4997, corrected for interstellar reddening

	1938	1956	1962
$I(\lambda 4363)/I(\lambda 4959, \lambda 5007)$ [O III]	0·0987*	0·0600†	0·0499‡
$I(\lambda 3343)/I(\lambda 3869, \lambda 3967)$ [Ne III]			0·00725§

* Aller (1941).
† Liller & Aller (1963).
‡ O'Dell (1963).
§ Aller & Kaler (1964).
Corrections for interstellar reddening from O'Dell (1963).

In Table II and in Fig 1 (*b*) appear the values of the unreddened ratio $I(\lambda 4363)/I(\lambda 4959, \lambda 5007)$ as derived from the two sets of photoelectric data and from Aller's 1938 photographic results, which are based on more extensive material than the 1939 (Page) results. The equation

$$\log \frac{I(\lambda 4363)}{I(\lambda 4959, \lambda 5007)} = -1 \cdot 15 - 0 \cdot 0122(t^y - 1950)$$

fits the points quite well with t^y measured in years.

The possibility of detecting a change in the integrated brightness of IC 4997 is slight, because the intensity of the λ4363 line is only about 3 or 4% of the total photographic intensity. Nevertheless, direct blue photographs of the nebula taken in past years with the 16 in. Metcalf telescope of the Agassiz Station of the Harvard College Observatory were compared with similar photographs made with the same instrument in 1963. No change was evident.

In summary, according to practically all observations made since the discovery of IC 4997, late in the nineteenth century, the λ4363 line of [O III] has been gradually and steadily weakening in intensity. Possible reasons for this change will now be discussed in detail.

3. *Discussion.* The comparatively high brightness (for a planetary nebula) of IC 4997 and its small angular diameter suggest that the nebula is relatively close to the earth and physically small in size. If one assumes that the nebula was formed by a single outburst of material from the central star, it is not difficult to suppose further that the mean density of the nebula is continually decreasing with time. Using such a model, the authors suggested earlier (Liller & Aller 1957) that the fading of the λ4363 line results from a steady decrease in electron density. That such a possibility exists can be seen from the equation relating the intensity ratio of the auroral and nebular lines of [O III] with the electron temperature, T_e, and the electron density N_e (see Seaton 1960):

$$\frac{I(\lambda 4363)}{I(\lambda 4959, \lambda 5007)} = \frac{1 + 3{\cdot}8 \times 10^{-4} N_e T_e^{-1/2}}{7{\cdot}1 \exp(33\,000/T_e)}. \qquad (1)$$

Any decrease in N_e or in the electron temperature or in both will produce a decrease in the intensity ratio of the lines.

Recently, however, this conclusion was criticized by Gurzadian (1958) and by Vorontsov-Velyaminov (1960) who interpreted the weakening of λ4363 relative to Hγ as the result of a decrease in electron temperature. Gurzadian pointed out that the intensity of the [O III] line depends on the product $N_e N_{\mathrm{O\,III}}$, where the $N_{\mathrm{O\,III}}$ is the density of [O III] ions in the ^{3}P level, while the intensity of the Hγ line depends on N_e^2. (See Aller 1956, for instance.) Therefore, the ratio of the line intensities should vary as the ratio $N_{\mathrm{O\,III}}/N_e$. Gurzadian argued that this ratio would remain very nearly constant over a wide range of N_e. There does remain, however, a dependence of the intensity ratio on T_e, and from this Gurzadian drew his final conclusion.

As mentioned earlier, we believe it is risky to compare lines whose upper levels have been populated on the one hand by radiative processes and on the other by collisional excitation. In the words of Vorontsov-Velyaminov (1961), 'the use of the λ4363 : Hγ ratio in the calculation of T_e is unfortunate since it may depend on a variety of factors'. Departures from thermodynamic equilibrium affect the two types of excitation in different ways, and in a nebula which is almost certainly optically thick, the size of the departure will depend on the electron density.

We believe it far safer to deduce the physical conditions in IC 4997 from a comparison of lines produced in the same ion. In examining the observed data and their theoretical significance, we shall consider only the following intensity ratios in the derivation of our results: $I(\lambda 4363)/I(\lambda 4959, \lambda 5007)$ of [O III];

and $I(\lambda3343)/(\lambda3869, \lambda3967)$ of [Ne III]. The relationship between the electron density and temperature and the [O III] line intensity ratio is given by equation (1). The equation for [Ne III] is

$$\frac{I(\lambda3343)}{I(\lambda3896, \lambda3967)} = 2\cdot51 \frac{1+4\cdot48\times10^4\sqrt{T_e}/N_e}{1+1\cdot69\times10^6\sqrt{T_e}/N_e} \exp\left(-\frac{18\,600}{T_e}\right). \tag{2}$$

The constants for this equation have been taken from the work of Seaton (1953) and of Garstang (1951).

For the [Ne III] ratio, we take the intensity values quoted by Aller & Kaler (1964), whose photometry is calibrated in part by the photoelectric results of O'Dell (1963). Because the $\lambda3967$ line is blended with Hϵ, it was necessary to substract the predicted Hϵ, as derived from the observed Balmer decrement, from the measured sum of the two intensities to arrive at an intensity for the [Ne III] line.

Table II lists both the neon and oxygen line ratios. The [O III] data should provide us with reliable information on the size of the various changes taking place in IC 4997. The [Ne III] ratio, which is perhaps less well determined than the [O III] ratio because of the more difficult photometry involved, should assist in evaluating the absolute size of the electron density and the electron temperature as of 1962.

Another approach to the problem uses the intensity of the Balmer continuum which was observed photoelectrically in 1956 with a pass band of 19 Å. This measurement should be reliable since there are no lines of appreciable intensity in the neighbourhood of $\lambda3647$. Furthermore, because of the high density of the nebula, the two-photon continuum is strongly suppressed (Seaton 1955). For a uniformly dense H II region, a model which we will adopt for IC 4997, the surface brightness, S_{Bac}, in units of flux of 20 Å at $\lambda3647$ is related to the ion density, N_i, the electron density, N_e, and electron temperature, T_e, by the equation (Aller 1956)

$$S_{\mathrm{Bac}} = 3\cdot56\times10^{-21} N_i N_e T_e^{-3/2} r, \tag{3}$$

where r is the radius of the nebula in centimetres. The Balmer continuum intensity (20 Å at $\lambda3647$) in 1956 was measured photoelectrically to be 3·6, relative to $I(\mathrm{H}\beta) = 10$; the corresponding unreddened value is 6·1. According to photoelectric measures made by O'Dell (1962), the mean surface brightness of IC 4997 in the light of Hβ, corrected for interstellar absorption, is given by the equation

$$\log S_{\mathrm{H}\beta} = +1\cdot24 - 2\log d, \tag{4}$$

where d is the angular diameter of the nebula in seconds of arc. Combining the two observational results with equation (3), one obtains

$$d^3 D = 3\cdot94\times10^8 N_e^{-2} T_e^{3/2}, \tag{5}$$

where D, the distance to IC 4997 in parsecs, is known only approximately. Some of the distance estimates are 1 450 pc (Vorontsov-Velyaminov 1960), 2 000 pc (Shklovsky 1956), and 11 700 pc (O'Dell 1962). Minkowski (private communication 1965) derives a distance of 1 820 pc. For the discussion that follows we shall adopt a distance of 1 500 pc with an uncertainty of a factor of two.

The observations summarized here and the first three equations yield the set of curves (Fig. 2) which indicate all possible values of $\log N_e$ and $\log T_e$. The three solid lines represent the observations of [O III] in 1938, 1956 and 1962. The dashed line represents the observation of [Ne III] in 1962. The dotted lines represent measurements of the Balmer continuum in 1956; the value of the angular diameter is indicated for each line.

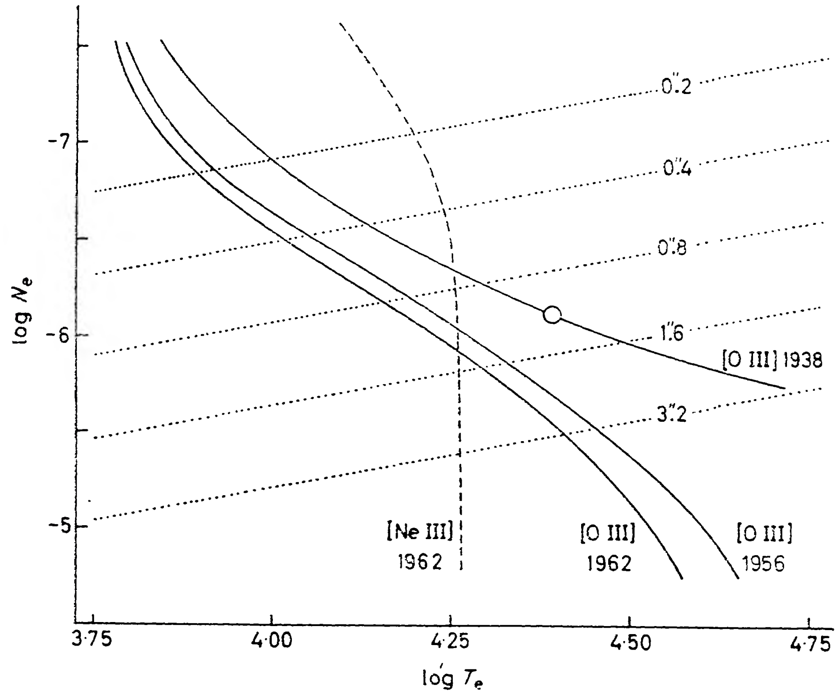

FIG. 2. *Possible values of log N_e and log T_e in IC 4997. The three solid lines represent the observations of [O III] in 1938, 1956 and 1962. The dashed line represents the observation of [Ne III] in 1962. The dotted lines represent measurements of the Balmer continuum in 1956; the value of the assumed angular diameter is indicated for each line. The open circle marks the calculated values of log T_e and log N_e for 1938.*

The problem is to find the specific path along which IC 4997 has movec since 1938.

One point on this evolutionary track which we can locate with reasonabl accuracy is the 1962 position which must be at the intersection of the 1962 [O III and [Ne III] curves. Here the predicted values of $\log N_e$ and T_e are 5·84 an 18 670° respectively. If we assign a $\pm 10\%$ uncertainty to the [Ne III observations of Aller & Kaler, a reasonable value in view of the extreme wavelengt of the λ3343 line, and a 1% uncertainty to the [O III] observations, we find corresponding range in T_e of $\pm 3{\cdot}9\%$ ($\Delta T_e = \pm 760°$) and in N_e of ± 11% ($\Delta \log N_e = \pm 0{\cdot}047$).

This location in the N_e–T_e plane is reasonably consistent with the diamet measurements of Seaton & Osterbrock (1957) and of Wilson & O'Dell (1962 Taking the distance to IC 4997 as 1 500 pc, we find that the spectrophotometr data plotted in Fig. 3 predict a mean angular diameter of 1″·35 or a linear diamet of $1{\cdot}51 \times 10^{16}$ cm (1 010 a.u.). If we should take a smaller value for the distanc we would be led to a larger value of d as equation (5) shows. However, becau the diameter is raised to the power 3, a moderate uncertainty in the distance leads to only a small uncertainty in *d*. Hence, if we allow a range in the distance of a factor of two, then we are left with a range of possible values of *d* from 1″·70 to 1″·07. The estimated range of uncertainty arising from the spectrophotometry alone is 0″·06.

Although we do not know what the value of the [Ne III] ratio was in 1938, we can estimate where IC 4997 must have been on the [O III] 1938 curve. We use the approximate expansion velocity, 15 km/s, found spectroscopically by Wilson & O'Dell (1962), and calculate the angular diameter in 1938, assuming it to have been 1″·35 in 1962. According to Schatzman & Kahn (1955), however, the radius of an H II region will increase at twice the rate of expansion of the individual atoms, as Liller (1965) has recently emphasized. Schatzman & Kahn do not allow for the possibility of rapid evolution of the exciting star. This could be important. Thus we calculate that the nebula was 1″·15 in diameter in 1938, 0″·20 smaller than in 1962. The corresponding values of $\log N_e$ and T_e are $6{\cdot}05 \pm 0{\cdot}048$ and $25\,100° \pm 1\,020°$; this position is marked with an open circle in Fig. 2. The uncertainties are those which would arise from an uncertainty by a factor of two in the distance and the estimated errors of the spectrophotometry.

We have assumed here that equation (5) holds true for all years from 1938 to 1962. For this assumption to be valid, the coefficient of equation (4) must remain constant. Since this coefficient is, in essence, a measure of the integrated brightness of the nebula in the light of Hβ, it will in fact change only slowly with time, because the decreasing surface brightness is compensated to a large extent by the increase in diameter of the nebula.

Other ions which can be employed to give additional $N_e - T_e$ curves are [O II] and [N II]. Seaton (1960) gives formulae which include the intensities of the $\lambda\lambda$3727, 7320 and 7330 lines of [O II], and the $\lambda\lambda$5755, 6548 and 6584 lines of [N II]. If one plots the locations of these curves in the $N_e - T_e$ plane using O'Dell's 1962 photoelectric data (O'Dell 1963), one finds that [N II] passes 0·04 in $\log N_e$ below the 1962 intersection of [Ne III] and [O III], whilst [O II] gives an electron density two orders of magnitude lower. The lack of agreement of [O II] should not be too surprising since it almost certainly radiates in a much larger zone than [O III] and [Ne III]. It is perhaps more surprising that [N II] agrees so well with the other results, since this ion must radiate in a zone similar to that of [O II].

Recently Seaton (personal communication 1965) brought to our attention a paper by Hummer (1963) who calculates that cooling caused by the collisional excitation of hydrogen will prevent electron temperatures from rising above 20 000 °K in a pure hydrogen nebula. If Hummer's results apply here, then we must assume either that IC 4997 is slightly closer to the Earth or that it is expanding somewhat more rapidly than 15 km/s. For the remaining discussion, however, we will adopt the results given by Fig. 2.

Since we now know the approximate size and rate of growth of IC 4997, we calculate that the nebula came into existence 1802 ($^{+60}_{-95}$) A.D. It is at least curious, if not significant, that a 6th magnitude nova (WY Sge) was observed in 1783 by D'Agelet, only 12° away from the position which IC 4997 had in that year (Gould 1866). A blunder of this magnitude in D'Agelet's observations or in Gould's subsequent reduction seems unlikely, however.

Table III summarizes the above results. Since photometric observations of IC 4997 have been made over something like 15% of its life history, we are perhaps permitted to make a simple exponential extrapolation backwards in time to see what the initial conditions in the nebula must have been like. We find that $\log N_e = 7{\cdot}24$ and $T_e = 133\,000$ °K. Extrapolating ahead in time, we find that $\log N_e$ will equal 3·00, a typical value for a low surface brightness nebula, in about the year 2400. Although the angular diameter at that time is indeterminate, since we have information only on the current diameter of the H II region and not on the true extent of the gas, we can say that the nebula will at that time be at least 5″·3 in diameter.

TABLE III

Past history of the physical conditions in IC 4997

Year	Angular diameter	$\log N_e$	T_e(°K)
1802 $\begin{pmatrix}+60\\-95\end{pmatrix}$	0″	(7·24)	(133 000)
1938	1″·15	6·05	25 100
1962	1″·35	5·84	18 670

4. *Conclusions.* Spectrophotometric observations of IC 4997 made since 1938 indicate that the electron density is now decreasing at a rate of 22% per decade and the electron temperature is decreasing at a rate of 13% per decade. The conditions in 1965 must be that $\log N_e = 5{\cdot}81$ and $T_e = 18\,000$ °K. These results are in satisfactory agreement with the distance and diameter measurements believed to be the most accurate for IC 4997.

Undoubtedly more observations are needed, both spectrophotometric and astrometric, so that the future changes in the nebula can be followed. The interesting discovery by Razmadze (1960) that VV 8 has a λ4363 line which is brighter than Hγ, just as IC 4997 once had, should be followed up with precise observations such as O'Dell (1963) has made so that its future history can be plotted. IC 4997 and perhaps VV 8 join the very small number of astronomical objects whose evolution can be followed from year to year.

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