

PHYSICAL VARIATIONS IN THE PLANETARY NEBULA IC 4997

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Received 1981 June 18; accepted 1981 August 27

ABSTRACT

The planetary nebula IC 4997 has a spectrum which shows a variation in the $[\text{O III}] \lambda 4363/\text{H}\gamma$ line intensity ratio that ranges from 1.6 in 1938 to 0.68 in 1962. Approximate values for the electron temperature and electron density of IC 4997 in 1962 are calculated from line intensity ratios of O III and N II ions. The equation of thermal equilibrium is used to calculate the electron temperature and electron density of the nebula in 1938.

The changes in electron temperature and electron density in IC 4997 between 1938 and 1962 are then shown to be possible consequences of the physical expansion of the nebula and not necessarily due, as has previously been suggested, to a change in the temperature of the central star.

If the explanation offered here for the 1938 to 1962 variation of $[\text{O III}] \lambda 4363/\text{H}\gamma$ line intensity ratio is valid, the recent behavior of this line ratio suggests that the central star may have undergone an additional episode of mass loss.

Subject headings: nebulae: individual — nebulae: planetary

I. INTRODUCTION

IC 4997 is an almost stellar appearing planetary nebula noted for having a very high electron density. An additional unusual aspect of this planetary is that the ratio of the intensity of the forbidden $\lambda 4363$ line of $[\text{O III}]$ to that of $\text{H}\gamma$ has decreased consistently from the late 1930's to the early 1960's, and it may now be increasing (Feibelman *et al.* 1979).

Although there is general agreement that the high intensity of the $\lambda 4363$ line is caused by a high electron density (N_e) and/or a high electron temperature (T_e), there is considerable disagreement about the cause of the variability of this line. Gurzadian (1958), Vorontsov-Vel'yaminov (1960), Khromov (1962) and Feibelman *et al.* (1979) attribute the variability to a decrease in T_e caused in turn by a decrease in the central star temperature. According to Khromov (1962), the required stellar temperature decrease is 0.5% per year (300 K per year if the central star temperature is 60,000 K). Central stars are indeed known to significantly change their temperatures during the observable lifetimes of the nebular shells (e.g., O'Dell 1963; Pottasch 1978); if this change occurs uniformly over time, the central star temperature would be expected to increase approximately 100 K in 30 years. Hence, the required change is about two orders of magnitude larger than the anticipated change and in the opposite sense. Although such an extreme short term stellar temperature variation cannot be dismissed as a

possibility, perhaps especially for the central star of one of the very youngest of the planetary nebulae, such a variation is at least inconsistent with the generally accepted characteristics of longer term evolution of planetary nebulae central stars.

Aller and Liller (1966) also discuss possible reasons for the variability of $j(\lambda 4363)/j(\text{H}\gamma)$ in IC 4997 and conclude that the observed changes in this ratio can be explained by a decrease in both T_e (13% per decade) and in N_e (22% per decade). They suggest that the N_e decrease may be due to expansion, but they do not suggest a physical explanation for the change in T_e in the nebula.

The intention here is to show that the changes in nebular density and temperature, which occur naturally as a consequence of expansion and the maintenance of thermal equilibrium, are sufficient to explain the observed variation in $j(\lambda 4363)/j(\text{H}\gamma)$ from 1938 to 1962, and that changes in the central star characteristics are not required. In § II N_e and T_e are derived for 1962, the procedure used for determining the N_e, T_e dependence of $J(\lambda 4363)/j(\text{H}\gamma)$ is discussed, and the relation between N_e and T_e implied by invoking thermal equilibrium is examined. Conclusions and a final discussion are contained in § III.

II. N_e AND T_e CHANGES

Feibelman *et al.* (1979) summarize the observed changes in $j(\lambda 4363)/j(\text{H}\gamma)$ in IC 4997 with time.

Examination of the most reliable data shows that a significant decrease in $j(\lambda 4363)/j(H\gamma)$ occurred between the years 1938 and 1962 when the line ratio dropped from a value of 1.6 to 0.68. One may use

$$\frac{j(\lambda 4959) + j(\lambda 5007)}{j(\lambda 4363)} = \frac{8.32 \exp(3.29 \times 10^4/T_e)}{1 + 4.5 \times 10^{-4} N_e/T_e^{1/2}}, \quad (1)$$

$$\frac{j(\lambda 6548) + j(\lambda 6583)}{j(\lambda 5755)} = \frac{7.53 \exp(2.50 \times 10^4/T_e)}{1 + 2.7 \times 10^{-3} N_e/T_e^{1/2}}, \quad (2)$$

and

$$\frac{j(\lambda 5007)}{j(\lambda 4959)} = \frac{j(\lambda 6583)}{j(\lambda 6548)} = 3.0 \quad (3)$$

from Osterbrock (1974) along with O'Dell's (1963) fluxes for $\lambda 4959$ and $\lambda 4363$ of [O III] and for $\lambda 6583$ and $\lambda 5755$ of [N II] to compute possible N_e, T_e combinations for 1962. Since radio observations indicate a logarithmic extinction at $H\beta$, $c=0$ (Cahn 1976), while visual observations indicate $c=0.5$ (Ahern 1978; Kaler 1976; O'Dell 1963), two N_e, T_e curves were plotted for each ion, one using uncorrected line fluxes and the other with fluxes corrected following the procedure of Miller and Mathews (1972). These curves are shown in Figure 1. A value of 3.2 was used for the ratio of total to selective extinction (Crawford and Mandwewala 1976). The assumed amount of reddening is not critical, so a point midway between the four curves was chosen to represent approximate 1962 values for IC 4997 of $T_e=15,000$ K, $\log N_e=5.66$.

The equations of statistical equilibrium for the collisionally excitable levels of O III were used to derive the functional dependence of $j(\lambda 4363)/N(\text{O III})$ on N_e and T_e . Transition probabilities and collisional transition rates were taken from Osterbrock (1974). The variation of $j(H\gamma)/N_H$ was calculated by fitting a parabola through values of $j(H\gamma)/N_p N_e$ at various temperatures given by Osterbrock (1974) for Case B. These results were combined to give $j(\lambda 4363)/j(H\gamma)$ versus N_e and T_e , which was then used to determine possible N_e, T_e combinations in 1938 when $j(\lambda 4363)/j(H\gamma)=1.6$ (Fig.

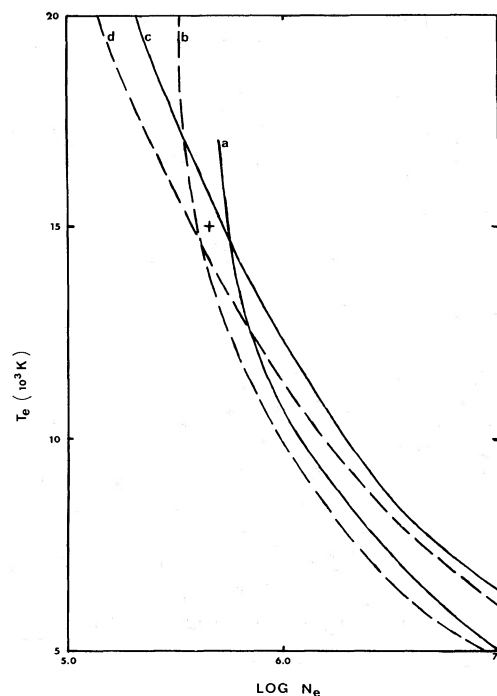


FIG. 1.—Possible N_e and T_e combinations computed from equations (1), (2), and (3) for (a) [N II] lines with $c=0.5$, (b) [N II] lines with $c=0$, (c) [O III] lines with $c=0.5$, and (d) [O III] lines with $c=0$. The cross represents adopted values for IC 4997 of $T_e=15,000$ K and $\log N_e=5.66$.

2). To combine $j(\lambda 4363)/N(\text{O III})$ and $j(H\gamma)/N_H$, a value of $\log N(\text{O III})/N_H = -3.96$ was used, determined by using the base 1962 values of N_e, T_e and the observed $j(\lambda 4363)/j(H\gamma)$ for that date. It is assumed that the value of $N(\text{O III})/N_H$ did not change significantly from 1938 to 1962.

The particular N_e and T_e values that prevailed in IC 4997 in 1938 have been determined by selecting from among the possible 1938 N_e, T_e combinations that one which satisfies the equation of thermal equilibrium in the nebula. Osterbrock (1974) gives specific expressions for free electron kinetic energy gains and losses in a

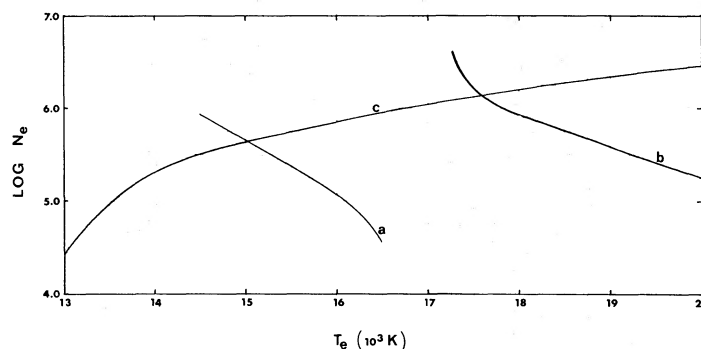


FIG. 2.—Combinations of N_e and T_e that satisfy (a) $j(\lambda 4363)/j(H\gamma)=0.68$, (b) $j(\lambda 4363)/j(H\gamma)=1.6$, and (c) thermal equilibrium.

static nebula in $\text{ergs cm}^{-3} \text{s}^{-1}$. With the assumption that energy losses occurring via collisional excitations are dominated by O III, the requirement of thermal equilibrium is given by

$$N_e^2 \alpha_B f k T_* = N_e^2 k T_e \beta_B + 1.42 \times 10^{-27} T_e^{1/2} N_e^2 \\ + N_3 (A_{32} h \nu_{32} + A_{31} h \nu_{31}) \\ + N_2 A_{21} h \nu_{21}, \quad (4)$$

where A 's are the radiative transition probabilities, α_B is the effective recombination coefficient for hydrogen, $f k T_*$ is the average kinetic energy of a photoelectron per ionization, N_2 and N_3 are the populations of the second and third excited states of O III, respectively, and β_B is the recombination cooling coefficient for hydrogen. The product $f k T_*$ was obtained by using the derived 1962 values of N_e and T_e and is assumed to be constant during the 24 year time interval. Cooling due to the nebular expansion does not make a significant contribution; hence, it is ignored in the energy balance relation.

In the limit of low density the thermal equilibrium relation yields a T_e versus T_* relation with no dependence on N_e . For higher density nebulae, however, the existence of nonnegligible collisional de-excitation introduces a dependence on N_e . Figure 2 shows that this latter case applies for IC 4997.

Figure 2 contains three sets of N_e, T_e combinations: (a) those that would result in $j(\lambda 4363)/j(\text{H}\gamma) = 0.68$, the 1962 value; (b) those that would result in $j(\lambda 4363)/j(\text{H}\gamma) = 1.6$, the 1938 value; and (c) those that satisfy the equation of thermal equilibrium. The intersection of (a) and (c) is, of course, $T_e = 15,000 \text{ K}$ and $\log N_e = 5.66$. The intersection of (b) and (c) will be the 1938 values of N_e and T_e : $T_e = 17,600 \text{ K}$ and $\log N_e = 6.14$. As the nebula expands and the density consequently decreases, the diminishing collisional de-excitations makes the "cooling" more efficient and the nebular temperature thus decreases. In 24 years, T_e dropped by 15% and N_e by 67%; these changes do not differ greatly from those inferred for different reasons by Aller and Liller (1966) which were mentioned in § I. The question remains of whether this significant density decrease over only a 24 year span which is implied by this analysis can reasonably be explained on the basis of a simple expansion.

III. DISCUSSION AND CONCLUSIONS

Pottasch (1980) finds an empirical relation between the ionized mass of a planetary nebula and its electron density. With the filling factor ϵ estimated to be 0.5 and $N_{\text{He}}/N_{\text{H}}$ taken as 0.1, Figure 3 of Pottasch (1980) yields a mass for IC 4997 in 1938 between $2 \times 10^{-5} M_{\odot}$ and $2 \times 10^{-4} M_{\odot}$. The mass of the nebula is given functionally by

$$M = 4/3 \pi r^3 \epsilon \left(1 + \frac{4 N_{\text{He}}}{N_{\text{H}}} \right) N_{\text{H}} m_{\text{H}}, \quad (5)$$

where m_{H} is the mass of a hydrogen atom, and M and r are the mass and radius of the nebula, respectively. Adopting the same values for ϵ and $N_{\text{He}}/N_{\text{H}}$ and taking $N_{\text{H}} = N_e/1.1$, equation (5) may now be solved for the radius in 1938 and, dealing with the same 1938 ionized mass, the radius of this mass in 1962. The lower mass limit yields $1.8 \times 10^{10} \text{ km}$ for r in 1938 and $2.6 \times 10^{10} \text{ km}$ for r in 1962, while the upper mass limit yields $3.9 \times 10^{10} \text{ km}$ and $5.6 \times 10^{10} \text{ km}$ for the 1938 and 1962 radii, respectively. The physical expansion velocity necessary to account for the N_e change from 1938 to 1962, assuming that N_e remains uniform throughout the nebula during the expansion, is then between 11 and 23 km s^{-1} . Wilson and O'Dell (1962) measured the expansion velocity to be approximately 15 km s^{-1} , which matches the values calculated here quite well.

In conclusion, it appears that, because of the small mass and high electron density of IC 4997, simple expansion will explain the large rate of decrease of N_e in the nebula and the consequent large variation of $j(\lambda 4363)/j(\text{H}\gamma)$.

It is interesting to note that if IC 4997 can be represented by a uniformly expanding sphere of constant total mass, the deduced density change between 1938 and 1962 implies that this planetary nebula came into existence in about 1884. That the total nebular mass may not remain constant is possibly suggested by the small but definite increase in $j(\lambda 4363)/j(\text{H}\gamma)$ which has occurred since 1962 (Feibelman *et al.* 1979). This increase could result from an increased mean density of the ionized portion of IC 4997 brought about by a recent episode of mass loss from the central star.

We thank William Kovach for helpful discussions.

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