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THE PLANETARY NEBULA IN THE FORNAX DWARF GALAXY

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ABSTRACT

A planetary nebula has been identified near the center of the Fornax dwarf elliptical galaxy. Quantitative spectrophotometry reveals that it is slightly reddened, and belongs to an intermediate-excitation class, with a normal helium abundance. Since the abundances of nitrogen, oxygen, and argon relative to hydrogen are all 2 to 3 times lower than in the Orion Nebula, the material in the nebula, which has a mass of at least 0.1 $M_{\odot}$, probably represents at least a second generation of processed matter. The implications of this conclusion are briefly discussed.

Subject headings: galaxies: individual — nebulae: abundances — nebulae: planetary

I. INTRODUCTION

Planetary nebulae provide one of the few ways in which abundances of elements in nearby extragalactic systems can be studied in detail. Dwarf systems in the Local Group are particularly interesting because of their cosmogonically uncertain place in the hierarchy of galaxies. The Fornax dwarf galaxy, at a distance of about 190 kpc, with a dominant old stellar component and a mass $\sim 2 \times 10^7 M_{\odot}$, is a good candidate for the detection of planetary nebulae. It is a system that has not been extensively studied till now.

II. DISCOVERY

The two dwarf elliptical galaxies in Sculptor and Fornax were searched for Hα emission objects. Pairs of direct photographs were taken on 098 emulsion with the 1.2 m UK Schmidt telescope. One was taken through a narrow-band interference filter centered on Hα, and the other through an RG 630 filter with an exposure time chosen so that continuum sources appeared with the same intensity on each of the plate pairs (exposure times were generally 180 and 12 minutes, respectively). Hα sources, which were expected to be brighter on the narrow-band plate, were searched for with a TV comparator designed by J. Bolton and built by the Australian National Radioastronomy Observatory. Hα emission objects were not detected in the Sculptor dwarf, but one was found near the center of the Fornax dwarf, and subsequent work on the 3.9 m Anglo-Australian Telescope (AAT) has shown that this is a planetary nebula. The position of the object is

$$2^{h}37^{m}45^{s}.1 \pm 0^{s}.7\,, \qquad -34°45'38'' \pm 2''\,(1950)\,,$$

and an identification chart which shows the comparison of the plate pair is given in Figure 1. The object is about 3'.5 from the center of the galaxy, which has an apparent radius of about 16'.

At the distance of Fornax the known planetary nebulae in the Magellanic Clouds would have Hβ fluxes between about $\log F(\mathrm{H}\beta) = -13.2$ and -14.1 ergs cm^{-2} s^{-1}. The Fornax planetary with an Hβ flux (next section) of $\log F(\mathrm{H}\beta) = -13.8$ ergs cm^{-2} s^{-1} is of similar intrinsic brightness to the Cloud planetaries. There are approximately 100 planetaries identified in these galaxies whose combined mass is about 6×10^9 $M_{\odot}$. One should thus expect to detect about 100/300 = 0.3 planetaries of this brightness in a galaxy with the mass of Fornax ($\sim 2 \times 10^7 M_{\odot}$, Hodge 1966) and about 0.05 in Sculptor ($\sim 3 \times 10^6 M_{\odot}$). Similarly, there is one (faint) planetary known in the galactic globular clusters, which have a combined mass comparable with that of Fornax. The number of known planetaries per unit mass in the extreme dwarf ellipticals is comparable with that in the Galactic globular cluster system and the Magellanic Clouds.

However, these statistics for Fornax apply only to the bright end of the luminosity function, since we estimate that our ability to identify planetaries extends only an approximate factor of 2 fainter than the one discovered with the present plate material.

III. SPECTROPHOTOMETRIC OBSERVATIONS

The planetary nebula was observed on several different nights with the image-dissector scanner (Robinson and Wampler 1973) attached to the Boller and Chivens spectrograph at the f/15 Cassegrain focus of the AAT. This spectrograph/grating combination gave a dispersion of ~ 180 Å mm^{-1} and a resolution ~ 9 Å. Absolute fluxes outside the atmosphere were computed by observing Oke (1974) white dwarfs on the same night. Our averaged scans of the planetary nebula are illustrated in Figure 2. The weak continuum visible there may be due partly to a central star in the nebula and partly to a nearby star in the field.

In Table 1 we present weighted average line strengths. Weak blended lines such as [O III] λ4363 and [N II] λ6584 were measured with a line profile

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TABLE 1

LINE STRENGTHS IN PLANETARY NEBULA

Ion	λ	Intensity Observed	Intensity Corrected for Reddening
[O II]...........	3727	23.5	25.2
[Ne III].........	3869	33.7	35.7
He I............	3889	13.6	14.4
Hε + [Ne III]....	3970	19.9	21.0
Hδ.............	4102	24.9	26.1
Hγ.............	4341	45.9	47.3
[O III]..........	4363	3.8	3.9
He I............	4471	5.4	5.5
Hβ.............	4861	100.0	100.0
[O III]..........	4959	201.7	200.8
[O III]..........	5007	583.6	579.5
He I............	5876	17.1	16.3
[N II]...........	6548	0.3	0.2
Hα.............	6563	314.4	290.1
[N II]...........	6584	7.8	7.1
He I............	6678	6.6	6.0
[S II]...........	6724	< 2.4	< 2.2
[Ar III]..........	7136	5.0	4.5
[O II]...........	7324	< 2.5	< 2.2

NOTE.—log $F(\mathrm{H}\beta) = -13.8 \pm 0.2$ ergs cm^{-2} s^{-1}.

fitting program which first established the instrumental profile and then computed a least-squares best fit to the blend. In this way, and because of a consistently observed asymmetry in the Hα profile, we can assert that a positive detection of [N II] λ6584 has been made. Examples illustrating this technique are presented in Figure 3. Our estimated accuracy for the relative line strengths ranges from 5% for the strongest lines to 30% for the weakest.

A heliocentric radial velocity of $+10 \pm 40$ km s^{-1} was measured for the nebula. This compares with $+40 \pm 30$ km s^{-1} for the globular cluster NGC 1049 in Fornax, measured by Humason, Mayall, and Sandage (1956).

IV. ANALYSIS

a) Reddening

The interstellar reddening has been estimated in the usual way by comparing the observed Balmer decrement with the theoretical values of Brocklehurst (1971) and assuming the Whitford reddening curve. From Hα, Hβ, Hλ, and Hδ a value of the reddening constant $c = 0.10 \pm 0.03$ is derived [where log $F(\mathrm{H}\beta)$ corrected = log $F(\mathrm{H}\beta)$ observed + c]. This is consistent with the apparently small amount of reddening observed in the Fornax globular clusters (Danziger 1973), and with its high galactic latitude.

b) Electron Density, Electron Temperature, and Mass

There are two line ratios which provide useful information about the electron density and electron temperature in the nebula, [O III] λ4363/λ5007 + λ4959 and the upper limit to [O II] λ7324/λ3727. In Figure 4 these are displayed in a T_e/N_e plot.

Since it is assumed that the planetary nebula is a member of the Fornax dwarf galaxy and therefore at a distance of 188 ± 40 kpc (Baade and Hubble 1939), it is possible to derive a relation between the mass of the nebula and the electron density through the equation

$$\mathrm{Mass}\,(\mathrm{H}^+) = 4\pi\ \mathrm{distance}^2\, F_c(\mathrm{H}\beta) m_{\mathrm{H}} \alpha(T_e)^{-1} N_e^{-1}\,,$$

where

F_c = corrected Hβ flux ,

m_{H} = proton mass ,

$\alpha(T_e)$ = recombination coefficient for hydrogen at an electron temperature T_e ,

N_e = electron density .

Lines corresponding to a constant ionized hydrogen mass of 0.1 and 1 solar masses are drawn in Figure 4.

Although the errors on the [O II] ratio limit are large (~100%), it appears from the figure that the nebular mass cannot be significantly less than 0.1 $M_\odot$. For the purpose of the abundance analysis that follows, it is assumed that the electron density is 4×10^3 cm^{-3}, corresponding to a hydrogen mass of 0.1 $M_\odot$.

c) Abundances

Lines of H, He, N, O, Ne, and Ar are present in the spectrum, and ionic abundances can be derived from these. Two methods of analysis have been used. In the first, the ionic abundances have been calculated using the temperature fluctuation scheme described by Peimbert and Costero (1969) but including the most recent calculations of atomic parameters (summary by Osterbrock 1974; Seaton 1975; Pradhan 1976). The temperature derived from the [O III] line ratio was assumed for each zone, and a fluctuation parameter $t^2 = 0.035$ was used. The results are shown in Table 2.

The second approach was to construct a series of model nebulae through the computer program described by Webster (1976), but updated with new atomic parameters and some additions, e.g., charge

TABLE 2

IONIC ABUNDANCES IN THE FORNAX PLANETARY NEBULA

Ion	Line (Å)	Abundance by Number Relative to H: Uniform	$t^2 = 0.035$
He^+.....	4471	0.112	0.110
	5876	0.121	0.116
	6678	0.160	0.154
O^+......	3727	0.14×10^{-4}	0.21×10^{-4}
O^{++}....	5007 + 4959	1.99×10^{-4}	3.00×10^{-4}
N^+......	6584	0.15×10^{-5}	0.21×10^{-5}
Ne^{++}...	3868	0.38×10^{-4}	0.60×10^{-4}
Ar^{++}....	7135	0.54×10^{-6}	0.77×10^{-6}
S^+......	6724	$< 0.12 \times 10^{-6}$	$< 0.17 \times 10^{-6}$

exchange. By matching these models with the observations, the oxygen was computed through the energy-balance equation (Flower 1969), and a value of O/H $= 2.6 \times 10^{-4}$ resulted. At the particular ionization level of the Fornax planetary this value is quite sensitive to the stellar energy distribution, and the good agreement with other calculations is somewhat fortuitous.

The models provide other information about the nebula. The [O III] 5007/Hβ ratio is sensitive to stellar abundance, temperature, and gravity, and there are too many variables to allow a unique self-consistent choice of these stellar parameters to be made. The stellar temperature appears to be between 35,000 K (zero Z) and 40,000 K (solar Z). The observed continuum flux is about 6 times too bright to fit these models and thus presumably comes mostly from background stars. The [O III] 5007/Hβ ratio is also sensitive to dilution, and quite small changes in the inner radius of the shell make a significant difference to the nebular ionization level. The presence of density fluctuations has less effect on the strength of lines from singly ionized atoms than at higher stellar temperatures, being comparable with general dilution effects.

The models are most valuable in determining the corrections to be applied to the classical analysis for the unseen ionization stages. To do this, the computed spectra for the models were analyzed by the Peimbert and Costero (PC) method and the results compared with the known input abundances. This should be an improvement over the simple fluctuation method because the relation between the temperature change (increasing away from the radiation source) and ionization level (decreasing from source) is included explicitly, and so similarly is the effect of small density changes (higher density gives generally a higher temperature, lower ionization, and more de-excitation).

i) *Helium*

In none of the models is there a significant amount of He^0 in the H^+ zone, so He/H $= He^+/H^+$. If one gives the value calculated from λ5876 three times the weight of that from λ4471 and from λ6678, a weighted mean of He/H $= 0.12 \pm 0.02$ by number results.

ii) *Oxygen*

Since there is a negligible amount of O^{+++} and O^0 in the H^+ zone, a correction to $O = O^+ + O^{++}$ is not required. In the presence of very severe density fluctuations with some $N_e > 3 \times 10^4$ cm^{-3}, some collisional de-excitation of $O^{++}\ {}^1D$ may occur and the electron temperature will be overestimated. This will lead to an underestimate of the abundances from forbidden lines which should be regarded as lower limits if such high densities are suspected. The absolute values of O/H calculated in the models with $t^2 = 0.035$ are up to 60% greater than input in the uniform model, implying a smaller t^2, but in the models with condensations the error is only 10%. There does not seem to be any plausible situation in which it could be much lower than this, as most errors of observation or analysis would tend to make it higher.

iii) *Nitrogen*

The nitrogen abundance must be calculated from N^+ by comparison with O^+ and O^{++}. Balick and Sneden (1976) derive a correction factor f of between 2.2 and 2.7 in the equation

$$N/H = O/H N^+/O^+ f ,$$

whereas Peimbert and Torres-Peimbert (1977) believe it is close to 1. We find the f appropriate to the PC method to be 0.8 ± 0.1 from seven models with a range of abundance and stellar temperatures close to that in Fornax. However two models, one with a steep temperature gradient and one with condensations, gave $f = 1.6$ and 0.32, respectively. It appears that the best correction factor to apply is 0.8 with a formal error of a factor of 2, but an uncertainty even greater than this.

iv) *Neon, Argon, and Sulfur*

The Ne^{++} abundance is extremely sensitive to details of the stellar radiation field, and it would be misleading to try to correct for the unseen stages. The models do not provide a useful correction factor for S^+.

From models resembling the Fornax object we find

$$Ar/H = (Ar^{++}/O^{++})(O/H)(1 \pm 0.4) .$$

This leads to an Ar/O ratio about 3 times lower than in Orion, but it is worth noting that the [Ar III] line strengths in the Fornax planetary are very similar to those in galactic planetaries such as NGC 6826 and NGC 4593 and that the apparent deficiency in Ar relative to O may therefore not be significant.

The total abundances are given in Table 3. Published line intensities of two Galactic planetaries, the low ionization object K648 in the metal-weak globular M15 and the higher ionization object PK 49+88°1 in the halo, have been reanalyzed in the same way as Fornax to make comparison convenient. Their relations to other Galactic planetaries will be discussed in the next section. The region in Orion closest in ionization level to Fornax (Peimbert and Torres-Peimbert 1977) has been treated similarly. Previous analyses of Orion and the Sun are included.

V. DISCUSSION

We know from the observations of the globular clusters in Fornax by van den Bergh (1969) and Danziger (1973) that there is a component which is extremely underabundant in all the heavy elements, both CNO and metals, and perhaps exceeding the most extreme globular clusters in the Galaxy in its degree of heavy-element poverty. The example of the evolution and consequent CNO production in a star of 1.25 $M_\odot$ given by Torres-Peimbert and Peimbert (1971) seems to preclude the possibility that all of the

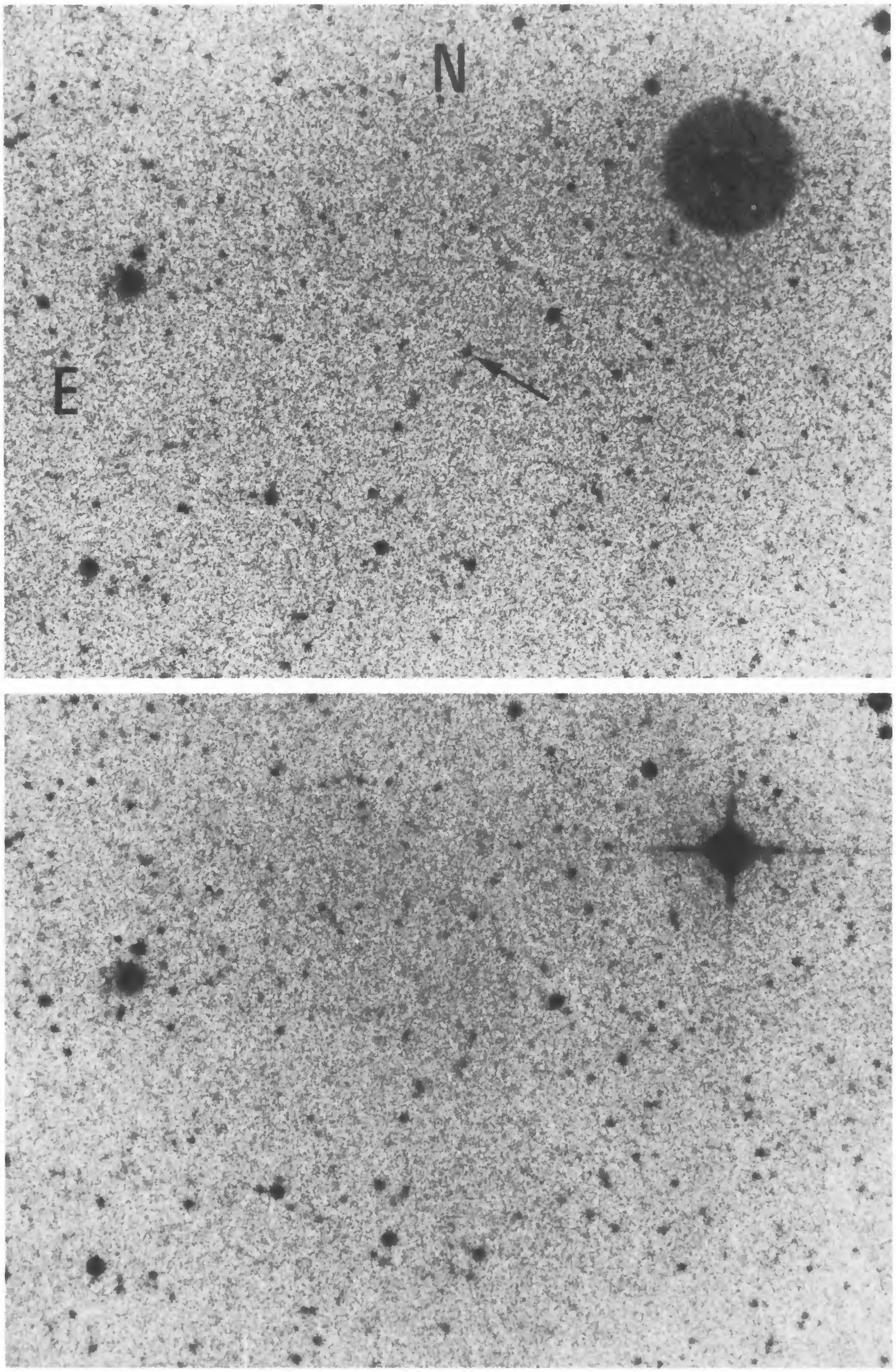

FIG. 1.—UK Schmidt plates of the field in Fornax containing the planetary nebula which is indicated by an arrow in the top photograph. The top photograph was taken through the Hα filter and the bottom one through an RG 630 filter, both on 098 emulsion.

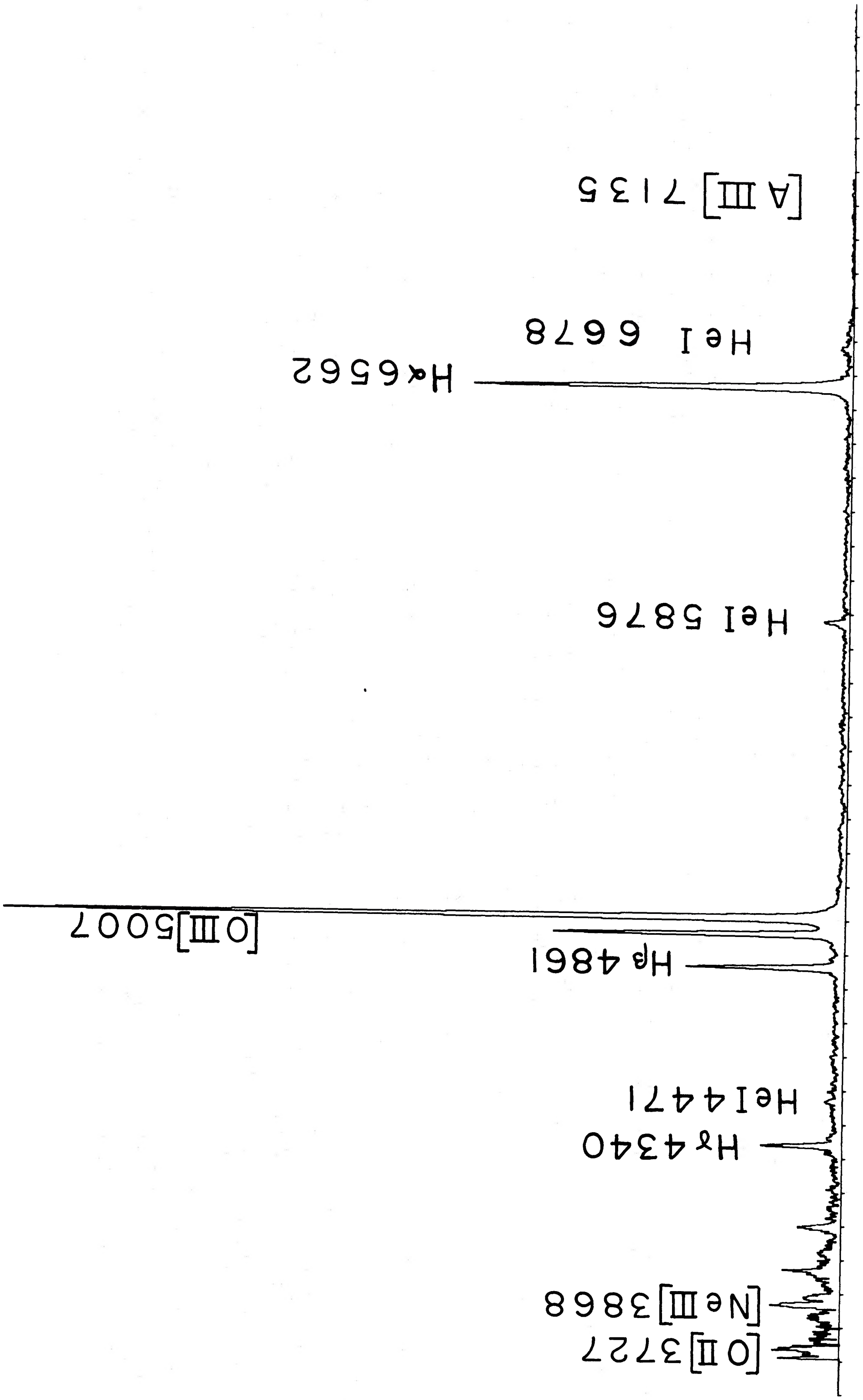

FIG. 2.—Summed spectral scans of the Fornax planetary nebula. Fluxes in ergs per 2 Å wavelength interval per second are plotted versus wavelength in angstroms.

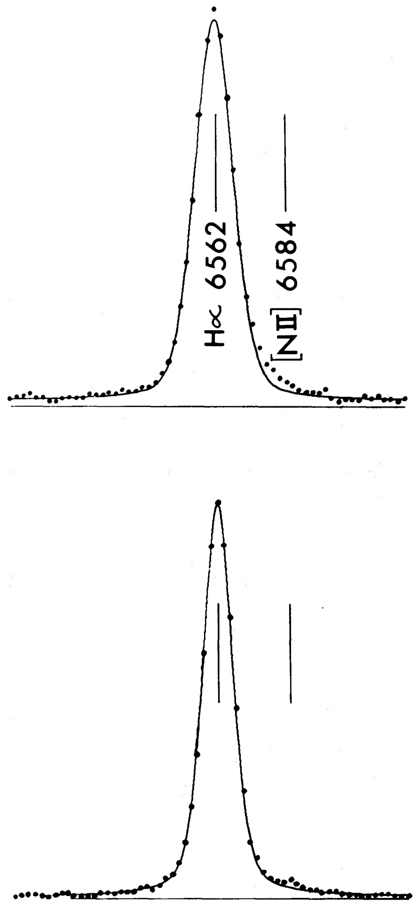

FIG. 3.—Examples of the profile-fitting technique used to establish the presence of [N II] lines. The top pair of profiles were obtained on one night; the bottom pair represent the sum of all nights, and hence the resolution is poorer. The left-hand solid profiles represent the best fit assuming only one line Hα is present; the right-hand profiles represent a fit assuming that [N II] lines are present at the known wavelengths, and where [N II] 6584/[N II] 6548 = 3. Line shapes are the same from right to left, but not of course from top to bottom. The vertical lines indicate the wavelength positions as marked.

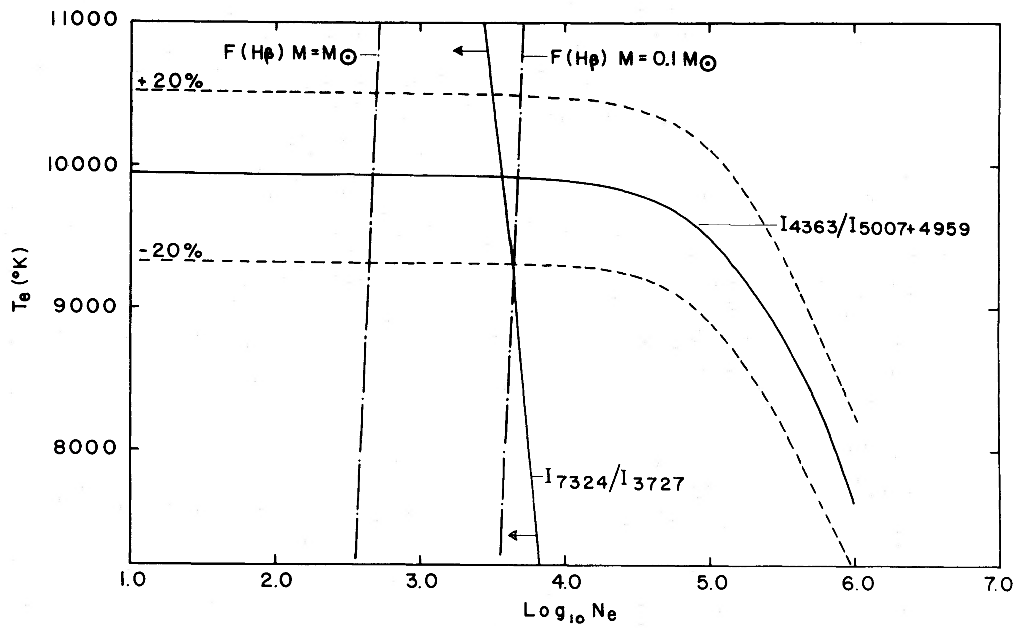

FIG. 4.—Allowed values of electron temperature and electron density for the Fornax planetary. The solid lines refer to relation set by the relative emission-line intensities. The dash-dot line defines the temperatures and densities consistent with the observed Hβ flux and two values of the nebular mass (§ IV*b*).

TABLE 3

Total Abundances by Number in the Fornax Planetary Nebula and Comparison Objects

Object	He/H	O/H	N/H	Ar/H	References
Fornax..........................	0.12	3.21×10^{-4}	2.56×10^{-5}	0.82×10^{-6}	1
K648 (in M15)....................	>0.096	0.52×10^{-4}	$<0.23 \times 10^{-5}$	...	2
PK 49+88°1 (halo)...............	0.12	1.65×10^{-4}	2.54×10^{-5}	...	3
Orion IA.........................	>0.092	6.65×10^{-4}	3.88×10^{-5}	7.08×10^{-6}	4
All Orion Peimbert analysis........	0.10	5.62×10^{-4}	5.75×10^{-5}	5.01×10^{-6}	4
Solar...........................	...	5.89×10^{-4}	8.51×10^{-5}	...	5

References.—(1) This paper. (2) Peimbert 1973. (3) Miller 1969. (4) Peimbert and Torres-Peimbert 1977. (5) Lambert 1968.

much higher abundance observed in the planetary nebula could have been produced in the parent star in one generation. Since Ar is formed at even deeper levels in the core of a star than is O, the fact that the N and O abundances relative to Ar in the planetary nebula do not differ by more than a factor of 3 from the ratios observed for solar material is support for the same conclusion. This inference is especially strong for oxygen because the abundance is well determined and because essentially no enhancement is expected. It should be noted that qualitative empirical schemes have been proposed by Bessell and Norris (1976) to explain enhancements of *only* C and N in the envelopes of CH and CN stars observed in the globular cluster ω Cen. Therefore, insofar as it might be relevant to the production of C and N in the envelopes of red giants which later become planetary nebulae, there still seems to exist a contrast between the predictions of theoretical models and some observed empirical effects.

The following discussion has to be less convincing because our nitrogen abundance determination, and indeed all nitrogen abundance determinations in planetary nebulae, are uncertain because of the large correction for unseen stages of ionization. The fact that O/N ratios appear to behave in a somewhat ordered manner over a wide range of absolute abundances and nebulae of different excitation class provides some reassurance, though not proof, on this point.

In Figure 5 we show a plot similar to one presented by D'Odorico and Peimbert (1976) from which most of the data were taken. Because the slope in this plot is ~0.5 and not 1.0, this has been taken as evidence that the correlation of N abundance with O over a wide range of absolute abundances points to an N gradient buildup in the Galaxy through secondary processes, the N enhancement being based on the evolutionary life cycles of planetary nebulae (Torres-Peimbert and Peimbert 1971). This is discussed by Talbot and Arnett (1974). The presence of the Fornax planetary nebula on the correlation does not prove the case for secondary production of N observed in Fornax. However, if we accept the correlation for the Galactic planetaries as meaningful, then the presence of Fornax on this line as a result of a *primary* process would have to be due to chance. This follows because the locus of N/O points for nitrogen enhanced by a *primary* process would be a line of slope 1.0 in Figure 5, intersecting the illustrated line at the position of the Fornax nebula. It would also imply that the material in Fornax prior to this enrichment had an N/O ratio differing from that in the galaxy prior to its secondary enrichment.

The evolution of the Fornax dwarf galaxy remains a puzzle. Models calculated by Larson (1974) for low-mass systems suggest that Fornax might have had an initial mass of 1–2 × 10^8 $M_\odot$, and after some gravitational collapse it lost 90% of its gaseous mass as a result of its low escape velocity easily exceeded by galactic winds generated by supernovae. These models are successful in explaining the lack of a condensed nucleus in Fornax and other dwarf systems. But the

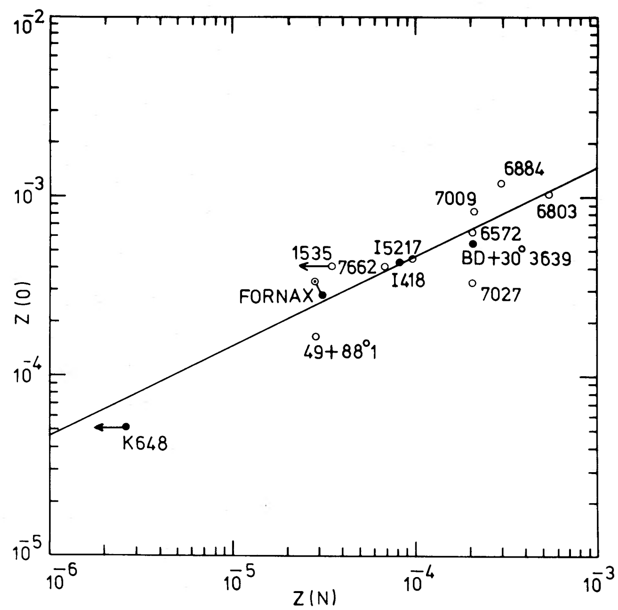

Fig. 5.—Oxygen and nitrogen abundances by number in galactic disk, halo, globular cluster, and dwarf spheroidal galaxy planetary nebulae. Pre–1975 atomic parameters have been used for consistency, and the dot-circle symbol for Fornax shows the shift produced by adopting new atomic collision strengths and ionization corrections. Filled circles represent objects with excitation classes equal to or lower than that of Fornax. The line is the enrichment line of slope 0.5.

predicted element production is low, and our *observed* high abundances and the large *observed* abundance inhomogeneity pose difficulties for these promising models as presently constituted. The range in metallicity observed among the globular clusters in Fornax by van den Bergh (1969) and Danziger (1973), and especially the recent work of Demers and Kunkel (1977) who observe a broad giant branch in the H-R diagram for the field stars in Fornax, could be further dramatic support for the conclusion that a large abundance gradient exists in the stellar component of the Fornax dwarf galaxy. It remains to be shown *directly* that this broad giant branch is associated with a range of abundances of the elements heavier than C, N, and O.

Although a similar phenomenon may be present in the large globular cluster ω Cen (Freeman and Rodgers 1975; Dickens and Bell 1976), it has not yet been observed in other dwarf elliptical galaxies. Without a completely speculative scenario the question "Why a range of heavy-element abundances in Fornax but not in the other dwarf systems?" remains unanswered.

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