Revista Mexicana de Astronomía y Astrofísica, Volumen 4, Agosto 1979

PHYSICAL CONDITIONS IN TWO HALO PLANETARY NEBULAE

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Received 1979 February 16

RESUMEN

Se presentan observaciones de líneas de emisión de la nebulosa planetaria en el cúmulo globular M15 (K648) y de la nebulosa planetaria en la dirección del polo norte galáctico 49 +88°1 (H4–1). A partir de estas observaciones se determinaron las abundancias de He, C, N, O, Ne, S y Ar con respecto a H. Se confirmó la deficiencia en O y Ne reportada previamente. En K648 el cociente de N/O es cuando menos tres veces menor que en la vecindad solar y en H4–1 el cociente de C/O es un orden de magnitud mayor que en el sol y que en la nebulosa de Orión. Este resultado indica que estrellas de muy poca masa están enriqueciendo en carbono el medio interestelar. Se encuentran deficiencias de Ne, S y Ar con respecto a O en H4-1; esto puede interpretarse ya sea como que en las primeras etapas de evolución de nuestra galaxia el enriquecimiento de oxígeno del medio interestelar ocurrió más rápidamente que el de neón, azufre y argón o bien que la estrella central ha contaminado la envolvente con oxígeno producido en su interior.

ABSTRACT

Photoelectric spectrophotometry of emission lines in the 3700–7400 Å region is presented for the planetary nebula in M15 (K648) and for the planetary nebula in the direction of the north galactic pole 49 +88°1 (H4–1). The abundances given in log N(X) with H = 12.00 are:

Object	He	O	C/O	N/O	Ne/O	S/O	Ar/O
K648	10.99	7.82	...	<−1.43	−1.03	<−1.6	<−2.3
H4–1	10.99	8.50	+0.89	−0.63	−1.70	−2.6:	<−3.3
PN of Type II	11.04	8.87	+0.63	−0.54	−0.61	−1.5:	−2.3:
Orion Nebula	11.00	8.75	−0.23	−0.99	−0.85	−1.55	−2.1:
Sun	...	8.92	−0.25	−0.93	−0.95	−1.69	...

The very high carbon abundance in H4–1 supports our previous contention that planetary nebulae are ejecting carbon rich material to the interstellar medium. The underabundances of Ne, S and Ar relative to O in H4–1, indicate either that the oxygen enrichment of the interstellar medium at the early phases of our galaxy proceeded faster than the Ne, S and Ar enrichment or that some O in the shell has been produced by the central star.

Key words: **ABUNDANCES — NEBULAE, PLANETARY — STARS, EVOLUTION.**

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I. INTRODUCTION

Peimbert (1978) has divided planetary nebulae, PN, into four types according to their chemical composition. In order of decreasing heavy element abundance the types are: I) He and N rich, II) intermediate population, III) high velocity, and IV) halo population. These types seem to be ordered by decreasing mass of the parent star (Peimbert and Serrano 1980). Webster (1978) has also identified the He and N rich PN as a distinct group.

Type IV PN are very important to establish the relative abundances in the interstellar medium of heavy elements that are not affected by the PN stellar evolution. It is also very important to study the enrichment of He, C and N by these objects because it provides us with observational restrictions for models of stellar evolution and of the chemical evolution of the interstellar medium; moreover this enrichment seems to vary for the various types of PN.

There are three established, and two proposed, type IV PN in the literature: a) K648 in the globular cluster M15 discovered by Pease (1928) and investigated by O'Dell *et al.* (1964), Peimbert (1973) and Hawley and Miller (1978); b) H4-1 discovered by Haro (1951) and studied by Miller (1969) and Hawley and Miller (1978); c) 108-76°1 discovered by Boeshaar and Bond (1977) and studied by them and Hawley and Miller (1978); d) N25 a planetary nebula, probably associated with NGC 1852 a red globular cluster in the LMC, studied by Webster (1976), e) an Hα emission object near the globular cluster NGC 6401 discovered by Peterson (1977), who suggested that this object could be a PN; however, Torres-Peimbert *et al.* (1980) have found that this object is not a PN.

Based on the λ4267 C II lines and assuming that they are formed only by recombination, Torres-Peimbert and Peimbert (1977) found that Type II PN have C/O and C/Ne ratios that are considerably higher than those of the Orion nebula and the sun indicating that some carbon produced by the PN parental star has been ejected into the shell; alternatively Bohlin *et al.* (1975, 1978) and Pottasch *et al.* (1978) based on the C IV λ1549 and C III λ1909 lines derive C/H ratios close to the solar one. The UV carbon abundance determinations depend considerably on the electron temperature and smaller values of T_e could produce agreement between the UV and the optical abundance determinations.

The discrepancy between the UV and optical determinations of C abundances has not yet been solved. The optical method is based on the assumption that λ4267 is formed only by recombination, this point has been extensively discussed by Torres-Peimbert and Peimbert (1977).

We decided to reobserve K648 and H4-1 to improve our knowledge of the galactic carbon abundance. In the population II objects any C produced by the central star would show up as larger C/O and C/Ne ratios than for type II PN or solar neighborhood objects like the Orion nebula and the sun.

II. OBSERVATIONS

The observations were carried out in 1977-1978 at KPNO with the 2.1 m telescope and the Image Intensifier Dissector Scanner, IIDS. The instrument and the observational procedure has been described elsewhere (Torres-Peimbert and Peimbert 1977). The dual entrance slits used were 0.30 $\times$ 0.98 mm where the first value is along and the second perpendicular to the dispersion; they correspond to 3.8 $\times$ 12.4 arcsec on the plane of the sky. For the cases reported here the slits were oriented east west; the separation between the centers of both slits corresponds to 99 arcsec. Two gratings, at a dispersion of 86 Å/mm, were used to cover the wavelength range of interest, one for 3400-5200 and the other for 5600-7400 Å. The half width resolution was 6-7 Å for both settings.

Each object was observed alternating the two slits. Measurements of the sky were obtained at the same time with the other slit. Each beam was treated independently and in all cases the sky was subtracted from the source. To correct the observations of K648 for the contribution of globular cluster stars we took several integrations with the object centered in the north south direction but at different places in the east west direction of the entrance slit; we also observed a very close bright star in order to subtract its contribution. The sensitivity of the system for all wavelengths was determined primarily from measurements of standard stars. In addition some PN and H II regions observed with single channel scanner were used as secondary standards. The calibration was derived from standard star fluxes by Stone

(1974) and Oke (1974) modified by means of the calibration by Hayes and Latham (1975). The continuum contribution to each emission line was subtracted by interpolating the continuum at both sides of the emission line.

In Table 1 we present the intrinsic line intensities in erg cm^{-2} s^{-1}, $I(\lambda)$, given by

$$\log I(\lambda)/I(H\beta) = \log F(\lambda)/F(H\beta) + C(H\beta)\ f(\lambda) \qquad (1)$$

where $F(\lambda)$ is the observed line flux corrected for atmospheric extinction and $C(H\beta)$ is the logarithmic reddening correction at $H\beta$. The reddening function, $f(\lambda)$, normalized at $H\beta$ is derived from the normal extinction law (Whitford 1958) and is also presented in Table 1. $C(H\beta)$ was determined by fitting the observed Balmer decrement, with the exception of $H\alpha$, to the one computed by Brocklehurst (1971) for $T_e = 10\,000$°K and $N_e = 10\,000$ cm^{-3}. The $H\alpha/H\beta$ ratio was adjusted to the theoretical one by correcting $F(H\alpha)$ according to equation (1) and by an additional gray shift which was applied to all the lines in the 5600 to 7400 Å range. This gray shift was always smaller than 0.10 in the log and is due to slight displacements of the observed position and/or changes in seeing conditions from night to night. The resulting accuracy of the blue to red line intensity ratios for bright lines is better than 0.04 in the log as can be tested by comparing the theoretical and observed He I (4472/5876) line intensity ratios.

Each object was observed with both settings in two different observing runs. The rms differences in the logarithm between the intrinsic line ratios $H10/H\beta$, $H9/H\beta$, $H\delta/H\beta$, $H\gamma/H\beta$ and 4472/5876 presented in Table 1 and the theoretical ones computed by Brocklehurst (1971, 1972) are 0.01, 0.02, 0.02, 0.01 and 0.02 respectively. The rms errors for the other line intensity ratios have been estimated by comparing results of different nights and for all cases are smaller than 0.04 in the logarithm with the exception of the measurement marked with a colon.

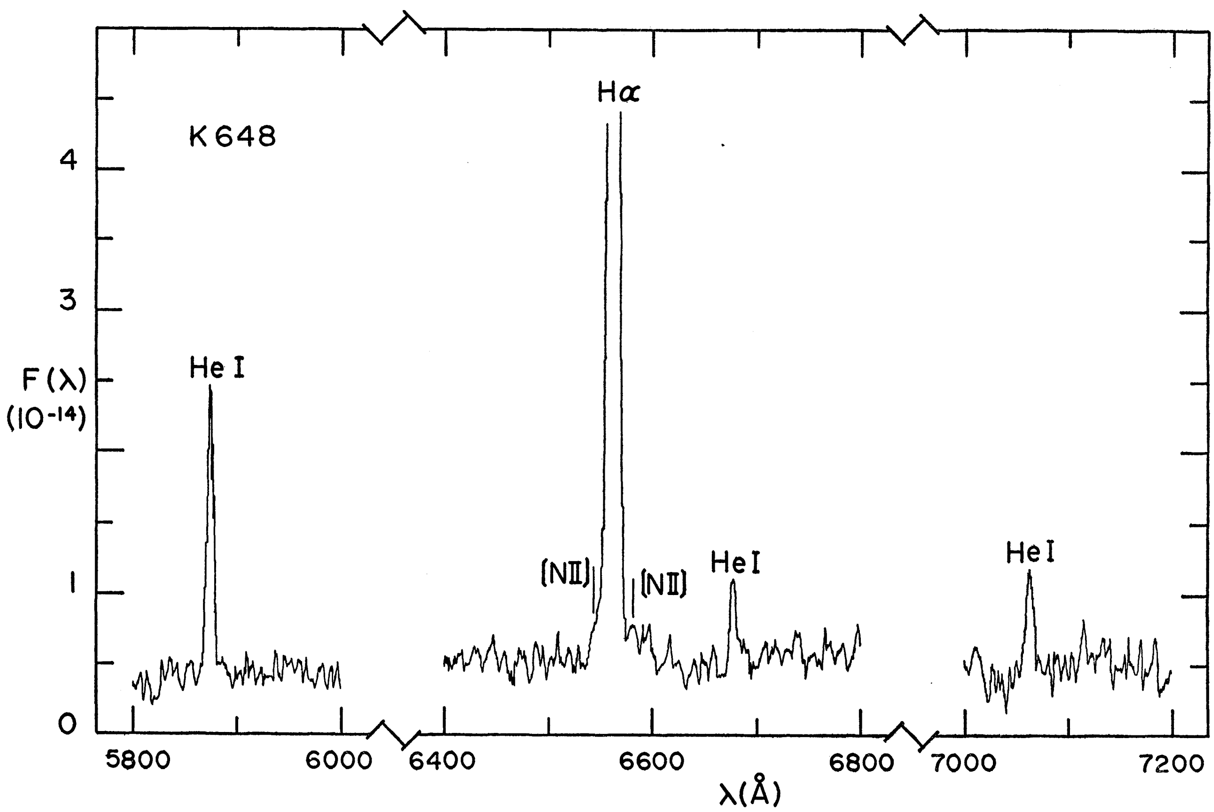

FIG. 1. Portion of a red spectrogram of K648 that does not show λ6584 of [N II] above the noise.

TABLE 1

LINE INTENSITIES, REDDENING CORRECTIONS AND FLUXES

λ	Ident.	f(λ)	K648	H4-1
3726+3729	[O II]	+0.315	-0.55	+0.33
3798	H 10	+0.290	-1.26	-1.28
3835	H 9	+0.280	-1.12	-1.15
3869	[Ne III]	+0.270	-1.11	-1.26
3886+3889	He I+H 8	+0.265	-0.72	-0.64
3967+3970	[Ne III]+H 7	+0.235	-0.79	-0.77
4026	He I	+0.225	...	-1.64
4069+4076	[S II]	+0.210	...	<-1.90
4097+4102	N III+Hδ	+0.200	-0.60	-0.59
4267	C II	+0.155	...	-1.86
4340	Hγ	+0.135	-0.34	-0.33
4363	[O III]	+0.130	-1.54	-1.07
4472	He I	+0.105	-1.33	-1.33
4686	He II	+0.045	<-1.96	-1.01
4861	Hβ	0.000	0.00	0.00
4922	He I	-0.015	...	-1.89
4959	[O III]	-0.020	-0.11	+0.38
5007	[O III]	-0.030	+0.36	+0.88
5198+5200	[N I]	-0.075	...	-2.01
5755	[N II]	-0.190	...	-1.69
5876	He I	-0.210	-0.90	-0.91
6300	[O I]	-0.285	...	-1.11
6363	[O I]	-0.300	...	-1.58
6548	[N II]	-0.330	...	-0.51
6563	Hα	-0.335	+0.45	+0.45
6584	[N II]	-0.340	<-1.68	-0.01
6678	He I	-0.360	-1.40	-1.50
6717	[S II]	-0.370	<-1.73	-2.17
6731	[S II]	-0.370		-2.15
7065	He I	-0.400	-1.33	-1.43
7136	[Ar III]	-0.410	<-1.64	<-1.98
7320	[O II]	-0.435	{-1.87:	-1.39
7330	[O II]	-0.435		-1.40
C (Hβ)			0.1	0.1
I (Hβ)			-12.08	-12.52

In general the agreement with previous observations by Peimbert (1973) and Hawley and Miller (1978) is good. The [N II]/Hα line intensity ratio in K648 is an important exception, as we derive a 2σ upper limit that is a factor of 3 smaller than the detection reported by Hawley and Miller; in Figure 1 we show the red region of one of our spectrograms and no [N II] line is evident, while $\lambda\lambda$6678 and 5876 which according to Hawley and Miller are of similar intensity or weaker than the [N II] line are clearly detected. Our result on the [N II] line is in agreement with the previous upper limit by Peimbert (1973). Our absolute fluxes for K648 are in excellent agreement with those of previous observers except that for H4-1 Hawley and Miller (1978) derive log F(Hβ) = $-$12.58 which is a factor of 2.2 higher than our result; part of the difference could be due to our small entrance slit, particularly if the object is elongated in the north-south direction. Figure 2 shows the wavelength region near Hα for H4-1.

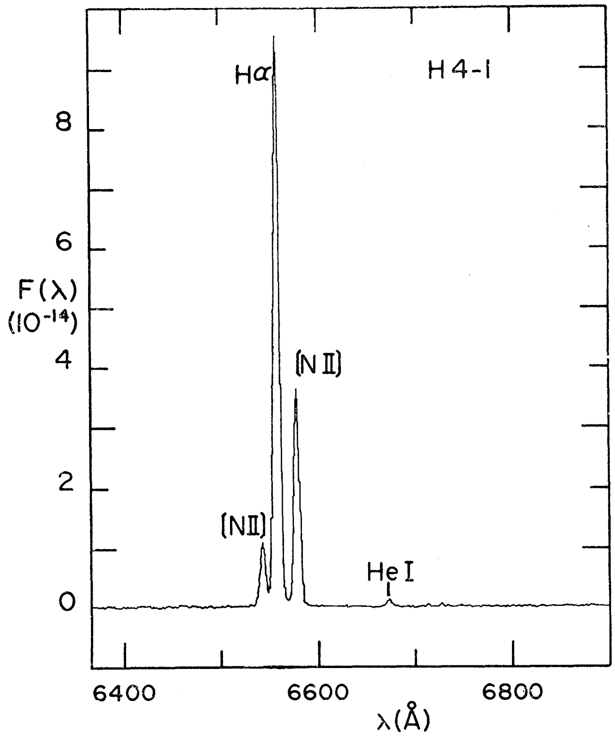

FIG. 2. Portion of the red spectrogram of H4–1, in this case $\lambda\lambda$6548 and 6584 are clearly resolved. Figure 1 has the same resolution.

III. TEMPERATURES, DENSITIES AND CHEMICAL ABUNDANCES

The relevant references to the atomic parameters used to derive electron temperatures, electron densities

TABLE 2

TEMPERATURES AND DENSITIES

	Line Ratio	K648	H4-1	Source
T_e (O III)	4363/5007	12000±400	11700±400	(1)
T_e (N II)	5755/6584	...	11100±450	(1)
T_e (O II)	{3727/7325, 3726/3729	10800^{+2600}_{-1200}	...	(1)
log N_e (O II)	3726/3729	3.3 ± 0.1	...	(2)
log N_e (O II)	3727/7325, 5755/6584	...	3.0±0.2	(1)
log N_e (S II)	6717/6731	...	2.9±0.1	(1)

(1) this paper, (2) O'Dell et al. 1964.

and chemical abundances are those used by Peimbert and Torres-Peimbert (1977) and Torres-Peimbert and Peimbert (1977) with the addition of the newer values for the collision strengths for S^+ computed by Pradhan (1978) (see also Czyzak and Krueger 1965) and the values for O° presented by Péquignot and Aldrovandi (1976) and by Wiese *et al.* (1966).

In Table 2 we present the [O III] and [N II] temperatures which for these objects are density independent. The K648 [O II] temperature is based on the density derived from the 3726/3729 ratio (O'Dell *et al.* 1964) and our 7325/3727 line intensity ratio, the accuracy of this temperature is low; however, it is in good agreement with T(O III). For the abundance determinations of K648 we made use of T(O III) only, while for H4-1 we used T(O III) for lines originating in regions of high degree of ionization and T(N II) for lines originating in regions of low degree of ionization. The 3726/3729 [O II] and the [S II] densities are temperature independent, while the H4-1 density derived from the [O II] and [N II] lines is of lower accuracy due to the larger number of lines involved, the larger correction for differential reddening and the assumption that the [N II] and the [O II] lines originate in the same region.

The ionic chemical abundances presented in Table 3 were derived assuming for the mean square temperature fluctuation, t^2, values of 0.035 and 0.00 which correspond to a moderate temperature variation and to a uniform temperature along the line of sight respectively (Peimbert and Torres-Peimbert 1977).

TABLE 3

IONIC CHEMICAL ABUNDANCES*

t^2	K648 0.00	K648 0.035	H4-1 0.00	H4-1 0.035
$N(He^+)/N(H^+)$	0.100	0.098	0.090	0.090
$N(He^{++})/N(H^+)$	<0.001	<0.001	0.008	0.008
log C^{++}	...	...	9.17	9.17
log N^+	<5.42	<5.50	7.16	7.25
log O^+	6.82	6.93	7.78	7.88
log O^{++}	7.63	7.76	8.18	8.33
log Ne^{++}	6.60	6.73	6.49	6.63
log S^+	<4.47	<4.56	4.39	4.48
log Ar^{++}	<5.11	<5.24	<4.82	<4.92

* with log H= 12.00

The total He abundances were obtained from

$$\frac{N(He)}{N(H)} = \frac{N(He^+ + He^{++})}{N(H^+)}, \qquad (2)$$

where the $N(He^+)/N(H^+)$ ratios were derived from the λ4472, λ5876 and 6678 to Hβ ratios giving them relative weights of 1, 2 and 1, respectively, corresponding to their relative intensities. The total O, N, Ne and C abundances were obtained from (cf. Peimbert and Costero 1969; Torres-Peimbert and Peimbert 1977).

$$\frac{N(O)}{N(H)} = \frac{N(O^+ + O^{++})}{N(H^+)} \frac{N(He^+ + He^{++})}{N(He^+)}, \qquad (3)$$

$$\frac{N(N)}{N(H)} = \frac{N(O)}{N(O^+)} \frac{N(N^+)}{N(H^+)}, \qquad (4)$$

$$\frac{N(Ne)}{N(H)} = \frac{N(O)}{N(O^{++})} \frac{N(Ne^{++})}{N(H^+)}, \qquad (5)$$

$$\frac{N(C)}{N(H)} = \left[1 + \frac{N(He^{++})}{N(He^+)}\right] \times \left[1 + \frac{3N(O^{++})}{10N(O^+) + N(O^{++})}\right] \frac{N(C^{++})}{N(H^+)}. \qquad (6)$$

The total abundances are presented in Table 4.

It has been found that equation (5) does not apply to gaseous nebulae of low degree of ionization (Torres-Peimbert and Peimbert 1977; Kaler 1978; Stasinska 1978). In Figure 3a we have plotted the Ne^{++}/O^{++} abundance ratio versus ionization degree for the PN observed by Torres-Peimbert and Peimbert (1977) and for H4-1 and K648. This figure suggests that for H4-1 and K648 equation (5) holds and that the Ne/O ratio is smaller in these objects than in PN of types I and II.

The Ar/O abundance ratio is given by

$$\frac{N(Ar)}{N(O)} = i_{cf}(Ar) \frac{N(Ar^{++})}{N(O)}, \qquad (7)$$

where i_{cf} (Ar) is the ionization correction factor that considers the fraction of Ar in the unobserved ionization stages. In Figure 3b we show the Ar^{++}/O abundance ratio versus ionization degree for the same

TABLE 4

TOTAL CHEMICAL ABUNDANCES

Object	t	He*	O*	C/O†	N/O†	Ne/O†	Source
K648	0.035	10.99	7.82	...	<-1.43	-1.03	(1)
K648	0.00	11.00	7.69	...	<-1.40	-1.03	(1)
K648	0.00	11.00	7.65	...	-0.54	-1.25	(2)
K648	0.055	11.00	7.67	...	<-1.38	-0.72	(3)
H4-1	0.035	10.99	8.50	+0.89	-0.63	-1.70	(1)
H4-1	0.00	10.99	8.37	+1.02	-0.62	-1.69	(1)
H4-1	0.00	11.03	8.34	...	-0.54	-1.62	(2)
Type II PN	0.035	11.04	8.87	+0.63	-0.54	-0.61	(4)
Type I PN	0.035	11.20	8.8	...	+0.2	-0.6	(5)
Orion Nebula	0.035	11.00	8.75	-0.23	-0.99	-0.85	(6)
SMC	0.035	10.89	7.99	...	-1.50	-0.86	(7)
Sun	...	...	8.92	-0.25	-0.93	-0.80	(8),(9)

* given as log N(X)/N(H)+12

† given as log N(X)/N(O)

(1) this paper; (2) Hawley and Miller 1978; (3),(5) Peimbert 1973, 1978; (4) Torres-Peimbert and Peimbert 1977;(6),(7)Peimbert and Torres-Peimbert 1977, 1976; (8) Lambert 1978; (9) Bertsch et al. 1972.

objects; from model computations it is known that in intermediate ionization objects,

$$-0.4 < \log O^+/O < -1.0,$$

almost half of the Ar is in the Ar^{++} stage (Rodríguez 1973; Peimbert *et al.* 1974) We have estimated $i_{cf}(Ar)$ on the basis of the ionization structure models by Rodríguez and the Ar/O abundance ratios are presented in the abstract for $t^2 = 0.035$. The Ar/O ratio that we derive for Type II PN is in excellent agreement with those by Aller (1978) and Kaler (1978).

Hawley and Miller (1978), from the S^+ and S^{++} abundances for H4-1, have found that S is underabundant by a factor of 2 to 3. This determination is based on the very faint λ6312 S^{++} line that we did not detect (our upper limit is not in contradiction with the detection by Hawley and Miller) and on the relation

$$\frac{N(S)}{N(O)} = \frac{N(S^+ + S^{++})}{N(O^+)} . \qquad (8)$$

It has been found that this equation overestimates the sulphur abundance, particularly for objects of high degree of ionization (Pagel 1978; Stasinska 1978). We decided to try to estimate the S/O abundance ratio based only on the S^+ lines.

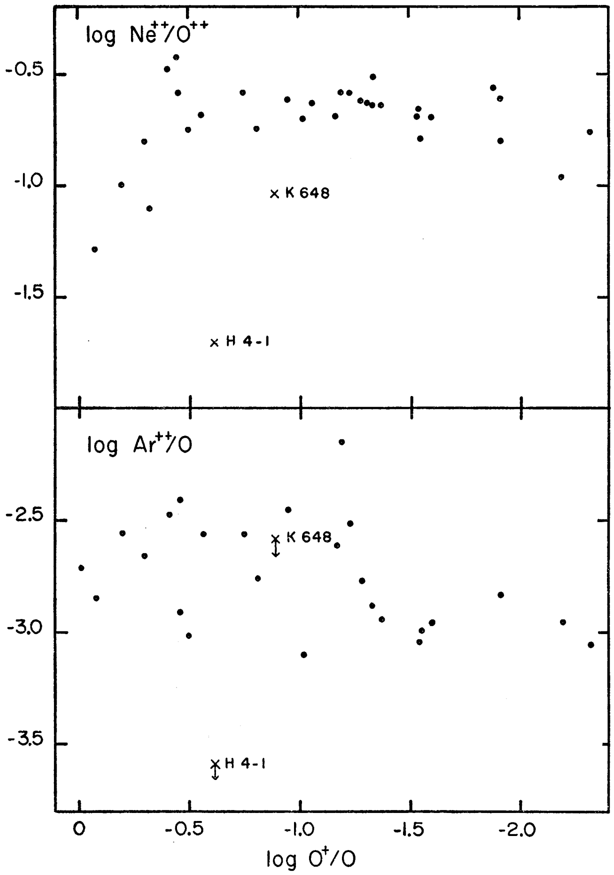

FIG. 3. Comparison of neon and argon for objects of different degree of ionization. Filled circles are disc planetary nebulae observed by Torres-Peimbert and Peimbert (1977).

In Figure 4a we show the S^+/O ratio versus ionization degree for the objects observed by Torres-Peimbert and Peimbert (1977) and for the two halo PN. There is a very pronounced trend, as expected, in the sense that the higher the degree of ionization the lower the S^+/O ratio. While the S^+/O upper limit for K648 is close to the mean relation, the S^+/O ratio for H4-1 is about one order of magnitude lower than the mean relation for objects with similar degree of ionization indicating a substantial sulphur underabundance. The fraction of sulphur in the S^+ stage of ionization amounts to a few percent only, so that the ionization correction factor is large and small ionization changes produce the large scatter present in Figure 4a.

To obtain a better estimate of the S/O abundance ratio we decided to compare S^+ with O° which has a similar ionization behaviour. Their relative abundances are given by (see references above)

$$\frac{N(S^+)}{N(O^\circ)} = \frac{I(6717 + 6731)}{I(6300)} \frac{1.25 \times 10^{-2}}{f(N_e, T_e)} \times \left(\frac{T}{10^4}\right) \exp(-1439/T), \quad (9)$$

where $f(N_e, T_e)$ considers the collisional deexcitation of the sulphur D levels and for the low density limit is equal to one. In Figure 4b we present the $N(S^+)/N(O^\circ)$ versus degree of ionization plot; the average value for the twelve disc PN is $\log N(S^+)/N(O^\circ) = -1.89$ while for H4-1 it is -2.72. In this figure there is no apparent trend between the abundance ratio and the ionization degree, but the scatter is still substantial. Part of the scatter could be due to different clumpiness or dilution factors; in this respect the three PN with the smallest N_e(rms): NGC 2371, NGC 2438 and NGC 3132 show values for $\log N(S^+)/N(O^\circ)$ equal to -1.31, -1.69 and -1.48, respectively. H4-1 is also a low density PN and the disc PN with closest density and degree of ionization is NGC 3132.

Based on the previous discussion we conclude that the N(S)/N(O) ratio in H4-1 is smaller than that of Type II PN by about one order of magnitude. The S abundance for Type II PN based on $N(S^{++})$ abundances and the solar S abundance (Lambert and Luck 1978) are also presented in the abstract.

IV. DISCUSSION AND CONCLUSIONS

From Table 4 it can be seen that the N(He)/N(H) ratio for Type IV PN is higher than the pregalactic value,

$$\log N(He)/N(H) + 12 = 10.87 \pm 0.02$$

(Peimbert and Torres-Peimbert 1976; Lequeux *et al.* 1979), and that the ratio increases with decreasing PN Type. For PN of Types IV, III and II most of the increase is due to the higher N(He)/N(H) ratio from which the PN stellar progenitor was formed and only a small amount is due to the He produced by their own evolution. On the other hand, for PN of Type I a substantial amount of helium is produced by their progenitor stars. A detailed discussion of this

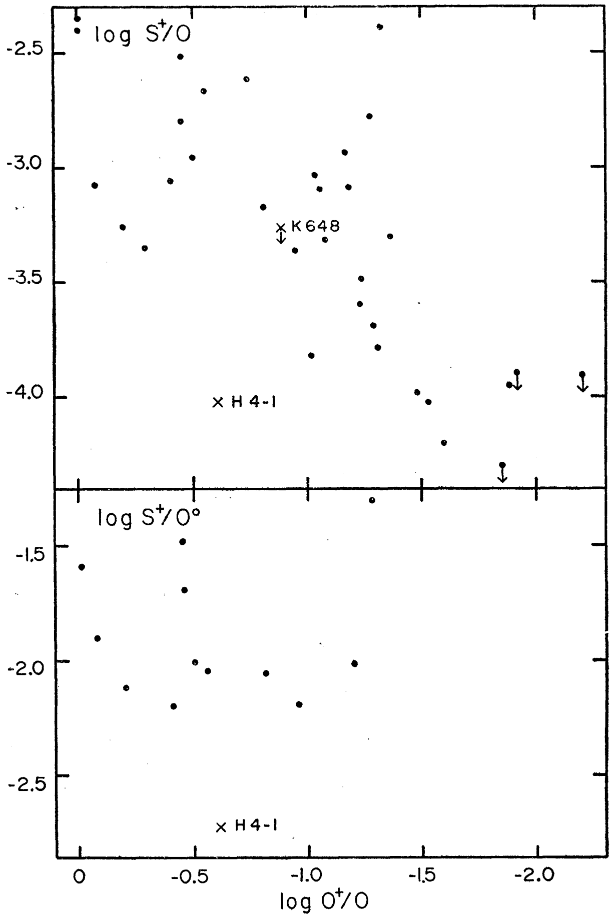

FIG. 4. Comparison of the sulphur to oxygen ratio for objects of different degree of ionization. The systematic effect on the S^+/O ratio due to the S ionization degree is not present on the S^+/O^0 ratio. Symbols are the same as in Figure 3.

problem is given elsewhere (Peimbert and Serrano 1979).

The very high C/O and C/Ne ratios in H4-1 indicate that indeed PN are ejecting carbon rich material to the interstellar medium as proposed by Torres-Peimbert and Peimbert (1977). The over-abundance of C indicates that products of He burning are present in the PN shell and therefore that some O contamination is also possible. The similar O/H and O/Ne/S/Ar abundance ratios in Types I and II PN and H II regions of the solar neighborhood indicate that the O contamination of the ejected shell, if present, is considerably smaller than the C contamination. The O/C ratio in H4-1 indicates that at most 11% of the freshly produced C has been converted into O.

N25 in the LMC shows a N/H underabundance of a factor of 10 to 20 relative to the solar neighborhood value (Webster 1976). The N25 N/H ratio is smaller by a factor of 3 to 6 than those of the LMC H II regions (Peimbert and Torres-Peimbert 1974; Dufour 1975; Aller *et al.* 1977; Pagel *et al.* 1978). This difference is in agreement with the idea that N25 is a Type IV PN since Types I and II have N/H values larger than those of galactic H II regions and only K648 has a N/H upper limit which is considerably smaller than those of galactic H II regions The abundances of H4-1 and K648 do not define a single trend. Low N/O is not a necessary condition for membership to Type IV PN, since it is not fulfilled by H4-1. Alternatively N25 might be a young PN of Type II with a very high electron density; in this case: the nebular [N II] lines are collisionally de-excited, the temperature derived from the N lines becomes smaller and the N/H and O/H abundances become larger.

The Ne, S and Ar abundances relative to O in H4-1 are one order of magnitude smaller than in disc PN and H II regions of the solar neighborhood. The Ne/O ratio in K648 is also a factor of two smaller than in disc PN, which might be significant. On the other hand, the PN in the Fornax Dwarf Irregular galaxy, which is underabundant in O/H by a factor of three, shows normal O/Ne/S/Ar ratios (Danziger *et al.* 1978).

K648 coupled with giant stars of the same cluster, shows O/N and O/metal effects that are consistent with previously suggested trends in galactic chemical evolution (e. g., Peimbert 1978, p. 219), whereas H4-1 shows quite a different pattern with C, N, O all enhanced relative to Ne, S, Ar. This could be due to evolution of the central star or alternatively it could just possibly be the first known case to exhibit a severe departure from the above-mentioned trends.

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