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CHEMICAL COMPOSITION OF TYPE I PLANETARY NEBULAE. COLLISIONAL EXCITATION EFFECTS ON HE I LINE INTENSITIES

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RESUMEN. Se presenta fotometría fotoeléctrica de líneas de emisión en el intervalo comprendido entre 3400 y 7400 A para trece nebulosas planetarias: NGC 650-1, NGC 2346, NGC 2371-2, NGC 2440, NGC 2818, NGC 7293, Hu 1-2, M1-8, M1-13, M1-17, M2-55, M3-3 y Me 2-2. A partir de estas observaciones se determinaron las abundancias relativas de H, He, C, N, O, Ne, S, Cℓ y Ar. Todos estos objetos son nebulosas planetarias de tipo I, esto es, ricas en He y N. Se determinó la no linealidad del detector usado, el IIDS. La excitación colisional a partir del nivel 2^3S de He I fue tomada en cuenta; se encontró que hay un proceso muy eficiente de despoblación del nivel 2^3S, probablemente ionización, que reduce considerablemente los efectos colisionales. Se dan argumentos que indican que la excitación colisional desde el nivel 2^3S es insignificante en regiones H II extragalácticas pobres en elementos pesados, lo cual implica que los efectos colisionales no afectan las determinaciones de la abundancia de helio pregaláctico o primordial.

ABSTRACT. Photoelectric spectrophotometry of emission lines in the 3400-7400 A region is presented for the following planetary nebulae: NGC 650-1, NGC 2346, NGC 2371-2, NGC 2440, NGC 2818, NGC 7293, Hu 1-2, M1-8, M1-13, M1-17, M2-55, M3-3 and Me 2-2. From these observations the relative abundances of H, He, C, N, O, Ne, S, Cℓ and Ar are derived. All these objects are Type I PN, i.e., He-N rich. The non-linearity of the detector used, IIDS, is determined. The collisional excitation from the 2^3S level of He I is considered; it is found that there is a very efficient process of depopulation of the 2^3S level, probably ionization, which reduces considerably the collisional effects. It is argued that the collisional excitation from the 2^3S level in metal poor extragalactic H II regions is almost negligible and that marginally affects the pregalactic, or primordial, helium abundance determinations.

Key words: ABUNDANCES — ATOMIC PROCESSES — COSMOLOGY — NEBULAE-PLANETARY STARS-EVOLUTION

I. INTRODUCTION

Planetary nebulae of Type I are objects with N(He)/N(H) ≧ 0.125 or log N(N)/N(O) ≧ -0.3, they form a distinct physical group that apparently originated from the most massive PN precursors (Peimbert 1978; Peimbert and Serrano 1980; Calvet and Peimbert 1983; Peimbert and Torres-Peimbert 1983). These objects are an important source of He and N enrichment of the interstellar medium and they might even be the most important N source (e.g. Peimbert 1987).

Recently Ferland (1986) has called attention to the effect that collisional excitation from the He I 2^3S state could have on the He^+/H^+ abundance ratios of PN and metal poor extragalactic H II regions. If this effect is neglected the derived $N(He^+)/N(H^+)$ ratios are overestimates of the real values. Ferland (1986), based on the results by Berrington *et al.* (1985),

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estimates that the He abundances in PN have been overestimated by as much as 50% and that the He abundances in metal poor extragalactic H II regions have been overestimated by as much as 30% which could have cosmological implications.

The collisional effects from the metastable 2^3S state depend strongly on the electron temperature and the electron density. In general PN of Type I are objects with high electron temperatures and high electron densities, therefore they are excellent objects to test these collisional effects.

To study the collisional effects from the 2^3S state and their implications we selected a group of Type I PN which are listed in Table 1. Also in Table 1 we present a list of references where the He and N excesses of these objects were reported.

TABLE 1. SOURCE LIST

Object	Source	Object	Source
NGC 650-1	1,2,3	M 1-8	1
NGC 2346	1,2,3	M 1-13	8
NGC 2371-2	1,3,4	M 1-17	8
NGC 2440	1,4,5	M 2-55	1,9,10
NGC 2818	1,4,6	M 3-3	1
NGC 7293	7	Me 2-2	1,11,12
Hu 1-2	1,2,3	...	...

1) Peimbert and Torres-Peimbert 1983, 2) Kaler 1979, 3) Aller and Czyzak 1983, 4) Torres-Peimbert and Peimbert 1977, 5) Shields *et al.* 1981, 6) Dufour 1984, 7) Hawley 1978, 8) this paper, 9) Kaler 1983, 10) Sabbadin and Hamzaoglu 1981, 11) Barker 1978, 12) Perinotto 1974.

II. OBSERVATIONS

The observations were carried out during 1979-1987 with the 2.1-m telescope at Kitt Peak National Observatory and the Intensified Image Dissector Scanner (IIDS). The observational procedure was described by Torres-Peimbert and Peimbert (1977). The dual entrance slits used corresponded to 3.8×12.4 arcsec on the plane of the sky; the slits were oriented east-west and the separation between the centers of both slits was 99 arcsec. Several gratings were used, covering the following wavelength ranges: $\lambda\lambda$3400-5200, 4800-6600, and 5600-7400 A. Each spectrum of about 20-mm length was recorded into 1024 channels. The FWHM resolution was 3.8 channels.

a) Correction for Non-linearity of the Detector.

The data were reduced to absolute fluxes via the standard stars of Stone (1977) and Oke (1974) and considering that the actual flux, F, is related to the instrumental signal, S, by the relation

$$S \propto F^{1+\beta} \qquad (1)$$

with $\beta = 0.07$.

There are several published and unpublished determinations of β for IIDS instruments: Davidson (1984) obtains $\beta = 0.03$ from emission lines over a strong continuum, $\beta = 0.05$ from emission lines over a weak continuum, and $\beta = 0.07$ from the [O III] 5007/4959 line intensity ratio assuming that the theoretical value is 2.88; Rosa (1985) obtains $\beta = 0.04 \pm 0.02$ from the 5007/4959 ratio assuming that the theoretical value is equal to 3.03; Wampler (1985) obtains $\beta = 0.04$ from the luminosities of bright quasars; Massey and De Veny (1986) from observations of a quartz lamp with a 1P21 photomultiplier and the KPNO IIDS found that $\beta = 0.0256 \pm 0.0028$.

We have determined β from three different line intensity ratios observed in H II regions and planetary nebulae: the [O III] 5007/4959 ratio, the [N II] 6584/6548 ratio and the He II 4686/4541 ratio.

In Figure 1 we present the data obtained in one observing season of the 5007/4959 line intensity ratio. The observations were made with the same entrance slits reported above, they have been corrected for differential reddening, which is almost negligible, and the count rates are below the level where coincidence corrections become important for the IIDS, at higher count rates the 5007 line saturates before 4959 and the S(5007)/S(4959) ratio becomes smaller. From the data in Figure 1 we find S(5007)/S(4959) = 3.134±0.024, which corresponds to $\beta = 0.080 \pm 0.007$ if we adopt the theoretical intensity ratio of 2.88 predicted from the transition

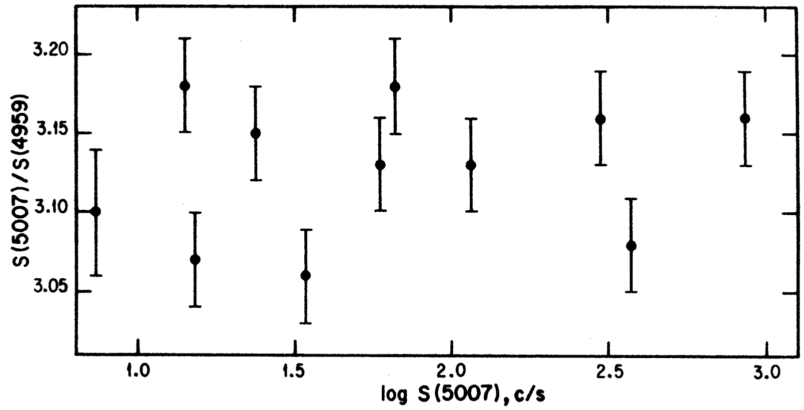

Fig. 1. Instrumental signal ratio of the [O III] lines, S(5007)/S(4959), for a group of planetary nebulae and H II regions.

probabilities computed by Nussbaumer and Storey (1981). Notice that there is no trend present in the [O III] ratio with the count rate over a range of more than two orders of magnitude.

From the observed 6584/6548 intensity ratio and the theoretical intensity ratio of 2.94, computed by Nussbaumer and Rusca (1979), we obtain $\beta = 0.072 \pm 0.012$. Finally from the He II 4686/4541 ratio observed in NGC 7662, NGC 7009 and Hu 1-2a and the theoretical ratio predicted by Hummer and Storey (1987) we obtain $\beta = 0.074 \pm 0.014$. The predicted 4686/4541 ratio is slightly density and temperature dependent; for NGC 7662 we adopted 29.0 which corresponds to T_e = 15 000 °K and N_e = 4000 cm^{-3} (Harrington *et al.* 1982); for NGC 7009 we adopted 29.5 which corresponds to T_e = 12 500 °K and N_e = 10^4 (Perinotto and Benvenuti 1981); for Hu 1-2a we adopted 28.2 which corresponds to Te = 19 500 °K and N_e = 5000 (this paper). The count rate for NGC 7662 and NGC 7009 is very large for the 2.1-m telescope and the IIDS, therefore for these two objects we partially closed the main mirror of the telescope to be below the level where coincidence corrections become important.

The easiest method to determine the non-linearity of a detector is based on the comparison of the observed and theoretical [O III] 5007/4959 line intensity ratio. Assuming that the [O III] transitions are due to magnetic dipole radiation, to a first approximation, it follows that

$$\frac{A(^1D_2 \rightarrow {}^3P_2)}{A(^1D_2 \rightarrow {}^3P_1)} = 3.0 \ ,$$

the corresponding flux ratio would be

$$\frac{F(5007)}{F(4959)} = 2.97 \ ;$$

additional effects were considered by Nussbaumer and Storey (1981) to correct the A values. These corrections reduce the ratio to 2.88. To have a theoretical ratio considerably higher than 2.88 we must have to assume that the corrections computed by Nussbaumer and Storey are in error by a large amount which is unlikely (Seaton 1986).

From theoretical considerations the errors expected in the [O III], [N II] and He II ratios are smaller than 2%, moreover the β values obtained from the three ratios are in very good agreement, therefore we conclude that most of the difference between the observed ratios and the theoretical ones is due to the non-linearity of the IIDS and not to the theoretical computations. In what follows we have adopted a value of β = 0.07 and we will consider that the theoretical computations are correct. By looking at the [O III], [N II] and He II ratios, it follows that the non-linearity effect is independent of wavelength and of intensity if the system is below saturation.

Llebaria *et al.* (1986) have found that the ESA Photo Counting Detector is nonlinear and that the observed count rate is related to the real flux by

$$S \propto 1.01 \ (F + 0.43 \ F^2) \ , \qquad (2)$$

for $S < 0.2$ counts px^{-1} s^{-1}. They have suggested that, on regions of high count rate, the phosphorescence at the output of the intensifier builds up a bright background which increases the probability that an event and its residual come above the detection threshold. They have also suggested that the same kind of non-linearity should be found in all photon counting detectors with phosphor screens.

To compare with observations not corrected by this effect we have to consider that the observations are given by

$$(S_\lambda + S_c + S_b) \propto (F_\lambda + F_c + F_b)^{1+\beta} , \qquad (3)$$

where F_λ is the emission line flux, F_c is the underlying continuum flux (made by nebular and stellar continua) and F_b is the background flux (due to night sky radiation and noise in the detector); therefore the intensity ratios of emission lines superimposed to strong continua are less affected than those of emission lines superimposed to weak continua, which explains the different values obtained by Davidson (1984); the maximum error due to the non-linearity effect is present in line intensity ratios of emission lines without underlying continua. Moreover, equation (3) implies that it is not possible to correct properly for this effect based only on the published line intensity ratios, it is necessary to re-reduce the original measurements. In any case, due to the presence of the different continua, the published emission line intensity ratios are affected by an exponent smaller than that given by equation (1).

From the observations studied by Rosa (1985) and under the assumption that the theoretical [O III] 5007/4959 ratio is 2.88 we obtain $\beta = 0.085 \pm 0.02$ in good agreement with our determinations and with that by Davidson (1984) based on the [O III] ratio.

The [O III] ratio of 3.09±0.05 obtained by Iye *et al.* (1987) from CCD observations gathered with a cooled CCD camera, CASPEC, at ESO is also in disagreement with the theoretical value probably implying the presence of nonlinear effects in that system.

The [O III] ratio of 2.889±0.014 derived by Mathis *et al.* (1985) with the SIT-vidicon at CTIO system is in excellent agreement with the theoretical predictions and implies that the vidicon system is linear to a very high approximation. This conclusion is in contradiction with the suggestion by Rosa and Mathis (1987).

The non-linearity of the IIDS detectors, if uncorrected, is responsible for small but systematic changes in the emission line intensity ratios that affect the determinations of various physical parameters: a) reduces the He/H abundance ratios, for example the pregalactic helium abundance derived by Rayo *et al.* (1982) should be increased from $Yp = 0.216$ to $Yp = 0.232$ (Torres-Peimbert *et al.* 1987); b) increases the logarithmic reddening corrections at Hβ, C(Hβ), by about 0.15; c) reduces the electron temperatures; d) increases the heavy element abundances for those determinations based on collisionally excited emission lines.

b) Line Intensities, Absolute Fluxes and Reddening Corrections.

In Table 2 we present the intrinsic line intensities given by

$$\log [I(\lambda)/I(H\beta)] = \log [F(\lambda)/F(H\beta)] + C(H\beta)\ f(\lambda), \qquad (4)$$

where $F(\lambda)$ is the observed flux corrected for atmospheric extinction and C(Hβ) is the logarithmic reddening correction at Hβ presented in Table 3. The F(Hβ) fluxes, also in Table 3, are given in erg cm^{-2} s^{-1}; notice that they correspond to the observed region through the entrance slit and not necessarily to the whole object. The contribution to the Balmer series due to recombinations of He^{++} is almost negligible and can be estimated from the observed intensity of λ4686 and the computations by Hummer and Storey (1987). The reddening function, $f(\lambda)$, normalized at Hβ was derived from the normal extinction law (Whitford 1958) and is also listed in Table 2. The C(Hβ) values presented in Table 3, were determined by fitting the observed Balmer decrement to the one computed by Hummer and Storey (1987) for case B, $T_e = 10\,000$ K and $N_e = 10\,000\ cm^{-3}$.

From line intensity ratios of two different nights we estimate that the standard deviation was 0.02 dex for Balmer line intensities relative to Hβ, and that $\sigma < 0.04$ dex for all line intensities relative to Hβ with the exception of those marked with a colon where $\sigma < 0.08$ dex. The standard deviation for the absolute flux at Hβ is 0.06 dex; this flux also includes λ4859 of He^{+}.

TABLE 2. LINE INTENSITIES

λ	ID	g(λ)	NGC 650-1	NGC 2346	NGC 2371-2	NGC 2440a	NGC 2440b	NGC 2818	NGC 7293	Hu 1-2a	Hu 1-2b	Hu 1-2c	M1-8	M1-13	M1-17	M2-55	M3-3	Me2-2
3444	O III	+0.390	-1.68	...	-0.71	-0.54	-0.54	...	...	-0.88	-0.89	-1.07	...	...	...	...	...	...
3726+3729	[O II]	+0.315	+0.79	+0.50	-0.08	+0.09	+0.41	+0.57	+0.80	-0.19	-0.20	-0.32	+0.51	+0.55:	+0.14:	+0.57	+0.45	-0.52
3835	H 9	+0.280	-1.15	...	-1.13	-1.08	...	...	...	-1.14	-1.15	-1.10	...	...	...	...	-1.18:	-1.10
3869	[Ne III]	+0.270	+0.24	+0.18	-0.01	+0.02	+0.15	+0.22	-0.02	-0.08	-0.09	-0.21	+0.15	+0.06:	+0.03:	+0.04	+0.03	-0.21
3889	HeI+H8	+0.265	-0.66	-0.69	-0.79	-0.76	-0.65	-0.67	-0.64:	-0.68	-0.69	-0.75	...	-0.67:	-0.75:	-0.67	-0.66:	-0.74
3967+3970	[Ne III]+H7	+0.235	-0.15	-0.24	-0.32	-0.33	-0.23	-0.17	-0.35	-0.39	-0.37	-0.45	-0.24	-0.32:	-0.36:	-0.27	-0.33	-0.50
4025+4026	HeII+HeI	+0.225	-1.63	-1.52	-1.77	-1.64	-1.58	...	...	-1.62	-1.62	-1.59	...	...	-1.65:	...	...	-1.43
4068+4076	[S II]	+0.210	-1.05	...	-1.34	-1.38	-1.29	-0.92	...	-1.28	-1.31	-1.36	-1.65	-1.37:	-1.04:	...	-1.82:	-1.85
4097+4102	N III+Hδ	+0.200	-0.54	-0.56	-0.53	-0.51	-0.50	-0.55	-0.57	-0.55	-0.56	-0.58	-0.53	-0.59:	-0.62:	-0.50	-0.55	-0.55
4267	C II	+0.155	-2.07:	-2.03::	-2.16	-2.31:	-2.34:	-2.36::	...	-2.71::	...	...	-1.95::	...	-2.07:	...	-2.06::	-2.09
4340	Hγ	+0.135	-0.30	-0.35	-0.33	-0.31	-0.31	-0.32	-0.34	-0.31	-0.32	-0.33	-0.34	-0.34:	-0.35:	-0.34	-0.33	-0.32
4363	[O III]	+0.130	-0.86	-0.96	-0.82	-0.62	-0.64	-0.62	-1.46:	-0.65	-0.65	-0.70	-0.80	-1.05:	-0.90:	-1.25:	-1.02	-1.20
4471	HeI	+0.105	-1.37	-1.29	-1.77	-1.60	-1.39	-1.37	-1.20:	-1.51	-1.50	-1.55	-1.36:	-1.26:	-1.28:	-1.24:	-1.30	-1.11
4541	HeII	+0.080	...	...	-1.47	-1.55	...	-1.54:	...	-1.50	-1.56:	...	...	...	...	...	...	...
4571	MgI	+0.070	-1.69	...	...	...	...	...	...	...	...	...	...	...	-1.69:	...	...	...
4634+4641	N III	+0.055	...	...	-1.42	-1.13	-1.21	...	...	-1.68	-1.76	...	...	-1.60:	-1.57:	...	...	-2.05
4686	HeII	+0.045	-0.40	-0.42	-0.05	-0.11	-0.29	-0.15	<1.60	-0.03	-0.03	+0.01	-0.24	-0.75:	-0.86:	-0.48	-0.47	-2.59
4711,13,15	[ArIV],HeI[NeIV]	+0.035	-1.83	-1.47	-0.79	-0.95	-1.07	-1.17	...	-1.02	-1.04	-0.97	-1.18	-1.57:	-1.49:	...	-1.60	-1.78
4725	[Ne IV]	+0.030	-2.59::	-1.95::	-1.67	-1.66:	-1.80::	-1.96::	...	-1.57	-1.58	...	...	...	...	...	...	-2.98::
4740	[Ar IV]	+0.030	-2.05	-1.81	-0.95	-0.99	-1.21	-1.40	...	-1.15	-1.14	-1.09	-1.47	-1.72:	-1.47:	...	...	-2.35
4861	Hβ	0.000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4922+4931	HeI+[O III]	-0.010	-1.88	-1.82	...	...	...	...	-1.78:	-2.04	-2.05	...	...	...	-1.85:	...	...	-1.58
4959	[O III]	-0.020	+0.62	+0.59	+0.55	+0.62	+0.67	+0.61	+0.24	+0.39	+0.41	+0.36	+0.61	+0.58	+0.69	+0.46	+0.47	+0.36
5007	[O III]	-0.030	+1.09	+1.06	+1.02	+1.09	+1.13	+1.08	+0.70	+0.86	+0.88	+0.83	+1.08	+1.04	+1.14	+0.92	+0.94	+0.79
5199+5201	[NI]	-0.075	-1.13	-1.35	-1.94	-1.16	-0.64	-1.12	-0.94:	-1.74	-1.84	...	-1.29	-1.13	-1.69	-1.24:	-0.87	-2.22
5411	HeII	-0.115	-1.46	...	-1.16	-1.19	-1.39:	-1.24	...	...	...	...	-1.22	-1.79:	-1.99:	...	...	...
5517	[Cℓ III]	-0.140	} -1.54	...	-1.97	-2.23:	-1.97:	...	...	...	...	...	...	-2.11:	-1.97:	...	...	...
5538	[Cℓ III]	-0.140		...	-1.96	-1.98:	-1.99:	...	...	...	...	...	...	-2.05:	-2.01:	...	...	...
5577	[O I]	-0.155	...	-1.48	...	...	-1.53:	...	...	...	...	...	-1.56	-1.68	-2.39	...	...	...
5755	[N II]	-0.190	-1.04	-1.47	-1.95	-0.95	-0.80:	-0.92:	-1.18:	-1.29	-1.33	-1.40	-1.13	-1.14	-1.32	-1.23:	...	-1.27
5876	HeI	-0.210	-0.89	-0.86	-1.33	-1.13	-0.89	-0.87:	-0.72:	-1.02	-1.03	-1.11	-0.87	-0.85	-0.83	-0.85	-0.90:	-0.63
6300	[O I]	-0.285	-0.52	-0.72	-1.45	-0.84	-0.49	-0.68	-0.31	-1.18	-1.28	-1.36	-0.84	-0.58	-0.74	-0.46	-0.95:	-1.67
6310+6311	HeII+[S III]	-0.290	-1.39	-1.79	-1.33	-1.59	-1.52	-0.98	...	-1.44	-1.47	-1.42	-1.60	...	-1.53	...	...	-2.19
6364	[O I]	-0.300	-0.98	-1.25	-2.01	-1.31	-0.88	-1.17	-0.85:	-1.67	-1.73	...	-1.28	-1.08	-1.24	-1.07:	-1.51:	-2.11
6548	[N II]	-0.330	+0.28	-0.02	-0.60	+0.26	+0.57	+0.20	+0.38	-0.26	-0.30	-0.37	-0.05	+0.11	-0.20	-0.08	+0.51	-0.30
6563	Hα	-0.335	+0.47	+0.45	+0.45	+0.46	+0.47	+0.43	+0.46	+0.46	+0.44	+0.47	+0.44	+0.42	+0.43	+0.47	+0.46	+0.45
6583	[N II]	-0.340	+0.76	+0.44	-0.13	+0.73	+1.03	+0.67	+0.85	+0.21	+0.17	+0.11	+0.45	+0.59	+0.32	+0.48	+0.97	+0.18
6678+6683	HeI+HeII	-0.360	-1.47	-1.42	-1.71	-1.59	-1.41	...	...	-1.54	-1.52	-1.59	...	-1.45:	-1.40:	...	-1.50:	-1.21
6717	[S II]	-0.370	-0.22	-1.59	-0.98	-1.23	-0.76	-0.43	-0.98:	-1.29	-1.32	-1.31	-1.04	-0.95	-0.90	-0.71	-1.30:	-2.57
6731	[S II]	-0.370	-0.28	-1.57	-1.00	-1.04	-0.71	-0.46	-1.13:	-1.07	-1.10	-1.13	-1.10	-0.87	-0.65	-0.73	-1.45:	-2.15
7006	[Ar V]	-0.395	...	...	-1.29	-1.20	...	...	...	-1.40	-1.45	-1.36	...	...	-2.31:	-1.10:	...	...
7065	HeI	-0.400	-1.58	...	-2.01	-1.50	...	...	...	-1.29	-1.27	-1.38	...	-1.48:	-1.19:	...	...	-0.79
7136	[Ar III]	-0.410	-0.50	...	-0.66	-0.63	...	...	-0.52	-0.97	-0.94	-0.93	...	-0.69	-0.73:	-0.60:	...	-1.02
7320	[O II]	-0.435	-0.68	...	-1.68	-0.88	...	...	-0.75:	-0.95	-0.88	-0.97	...	-1.02	-0.68:	-0.68:	...	-1.04

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TABLE 3. POSITIONS, Hβ FLUXES AND REDDENING CORRECTIONS

Object	Observed Region Relative to Center	-log F(Hβ)[a]	C(Hβ)
NGC 650-1	SW	12.43	0.35
NGC 2346	6"N	12.84	0.30
NGC 2371-2	SW	12.20	0.10
NGC 2440*a*	center	11.25	0.30
NGC 2440*b*	8"N	11.45	0.05
NGC 2818	S	12.68	0.20
NGC 7293	220"N,140"E	13.55	0.00
Hu 1-2*a*	center	11.59	0.65
Hu 1-2*b*	4"N	12.01	0.65
Hu 1-2c	6"N	12.70	0.60
M 1-8	center	13.10	0.85
M 1-13	center	12.30	0.90
M 1-17	center	12.26	1.05
M 2-55	center	13.66	1.20
M 3-3	center	12.84	0.30
Me 2-2	center	11.18	0.35

a. In erg cm^{-2} s^{-1}.

III. TEMPERATURES, DENSITIES, AND CHEMICAL ABUNDANCES

The relevant references to the atomic parameters used to derive electron temperatures, electron densities, and chemical abundances are those presented in the compilation by Mendoza (1983) unless otherwise noted. For the collision strengths of Ar IV we used the results by Zeippen *et al.* (1986), and for the effective recombination coefficients of H I and He II, we used the computations for case B by Hummer and Storey (1987).

a) Temperatures and Densities.

We present in Table 4 temperatures and densities derived from solutions to the forbidden line intensity ratios in the (N_e, T_e) - plane. The temperature errors correspond to 0.04 dex errors in the intensity ratios. The density errors, corresponding to 0.04 dex errors in the intensity ratios, are: of 0.17 dex for S II in the 2.2 to 4 log N_e range, of 0.15 dex for Cℓ III in the 2.8 to 5 log N_e range, and of 0.08 dex for Ar IV in the 2.8 to 5.2 log N_e range. Outside of these density ranges the intensity ratios are not density sensitive.

TABLE 4. TEMPERATURES AND DENSITIES[a]

	T_e [O III] (K)	T_e [N II] (K)	N_e [S II] (cm^{-3})	N_e [Ar IV] (cm^{-3})	N_e [Cℓ III] (cm^{-3})	N_e Adopted (cm^{-3})
NGC 650-1	12100±570	10000±270	310	2900	...	1000
NGC 2346	11500±500	9000±220	740	< 600	...	700
NGC 2371-2	13350±670	9800±270	530	410	2490	500
NGC 2440a	15000±800	11000±230	3300	4800	9940	4500
NGC 2440b	14150±670	9700±300	1090	1900	1920	1900
NGC 2818	15100±800	12450±400	500	< 600	...	500
NGC 7293	10300±400	8250±170	< 140	...	...	100
Hu 1-2a	19500±1000	13400±440	4950	5100	...	5000
Hu 1-2b	18500±1000	13400±440	4830	4600	...	4700
Hu 1-2c	18500±1000	13400±440	3420	> 760	...	3400
M 1-8	12800±670	12650±400	320	< 600	...	320
M 1-13	10900±450	10600±300	1200	> 1900	3910:	2100
M 1-17	11300±500	11100±330	5200	6400	1670:	5300
M 2-55	10250±400	10900±330	460	...	...	460
M 3-3	12000±570	(10400)	< 140:	...	...	300
Me 2-2	11550±520	10600±300	(43000)	...	...	40000[b]

(a) Assuming that the collisional effect on the He 4713 line is 37 % of the theoretical one.
(b) From Barker (1978), Isaacman (1984), Shaw and Kaler (1985), Aller and Keyes (1987).

b) Helium.

(*i*) Collisional Effects in the Helium Singlets and Triplets.

The collisional cross sections from the 2^3S state based on a 19 state R-matrix calculation (Berrington and Kingstone 1987) are very similar to those by Berrington *et al.* (1985) based on an 11-state R-matrix calculations for collisions involving states with principal quantum numbers, n, equal to 1 and 2; but for collisions to states with n = 3 the new results are from 1.4 to 1.8 times smaller for typical temperatures found in gaseous nebulae. The 19-state results imply that collisional excitation rates from the 2^3S state to states with n = 4 are reliable to about a factor of 1.6 and that only when the n = 5 transitions are taken into account their value would be reliable within a few per cent, alternatively the 19-state results for collisions to states with n = 3 should be reliable within a few per cent.

From steady state considerations involving the 2^3S level we find

$$N(2^3S) = \frac{N_e\, N(He^+)\, \alpha_{tri}(T_e)}{D_T} \quad , \qquad (5)$$

where

$$\alpha_{tri}(T_e) = 2.04\times 10^{-13}\, t_4^{-0.73}\ \mathrm{cm^3\ s^{-1}} \qquad (6)$$

is the effective recombination coefficient to the triplet series (Brocklehurst 1972), $t_4 = T_e/10^4$ K; N_e, $N(He^+)$ and $N(2^3S)$ are the electron, singly ionized helium and 2^3S state densities and D_T is the total depopulation rate given by

$$\begin{aligned} D_T(2^3S) &= A(2^3S,\ 1^1S) + [C(2^3S, 1^1S) + C(2^3S,\ 2^1S) + \\ &+ C(2^3S,\ 2^1P)] + D_i(Ly\alpha) + D_i(stellar) + D_i(coll) + D_e \\ &= D_A + D_C + D_i(Ly\alpha) + D_i(stellar) + D_i(coll) + D_e \quad , \qquad (7) \end{aligned}$$

where $A(2^3S,\ 1^1S) = 1.13\times 10^{-4}\ \mathrm{s^{-1}}$ is the Einstein transition coefficient (Drake 1971; Hata and Grant 1981), D_C is the triplet-singlet exchange collision rate, and can be approximated as (Berrington and Kingston 1987)

$$D_C = 3.50\times 10^{-8}\ t_4^{0.24}\mathrm{cm^3\ s^{-1}} \quad , \qquad (8)$$

over $1 \leqq t_4 \leqq 2.0$, where we did not consider terms involving levels with n = 3 since they contribute with less than 3% to D_C over the temperature range of interest, D_i (Ly α) denotes the ionization rate from the 2^3S state due to the Lyman α radiation field, D_i (stellar) denotes the ionization rate from the 2^3S state due to direct stellar radiation (e.g., Capriotti 1967; Persson 1972), D_i(coll) denotes the collisional ionization from the 2^3S state, and D_e denotes the excitation rate of doubly excited auto-ionizing states of helium by line emission from the central star (Robbins 1968*b*).

Two other processes to depopulate the 2^3S level have been studied by Persson (1972) and found to be negligible for PN: a) excitation transfer reactions of the type

$$He(2^3S) + X \rightarrow He(1^1S) + X^* \ ,$$

$$X^* \rightarrow X + h\nu \quad ,$$

where X is some ground state atom or ion which possesses an excited state (*) as far above ground as He I (2^3S) lies above He I (1^1S), and b) the Penning ionization process

$$He(2^3S) + X \rightarrow He(1^1S) + X^+ + e^- \quad ,$$

where X is any atomic system with IP < 19 eV.

For the time being we will assume that the D_i(Lyα), D_i(stellar), D_i(coll), and D_e terms are negligible in comparison with D_A and D_C, we will come back to this assumption later on.

From these approximations, equation (5) can be written as

$$\frac{N(2^3S)}{N(He^+)} = \frac{5.82\times 10^{-6}\ t_4^{-0.97}}{(1 + 3229\ t_4^{-0.24} N_e^{-1})} \ ; \qquad (9)$$

most of the difference with the equation (4) derived by Ferland (1986) is due to the inclusion of the $C(2^3S, 1^1S)$ term in D_C.

The collisional rates for the $1.0 \leqq t_4 \leqq 2.0$ range can be approximated as follows

$$C(2^3S, n^1L) = p\, t_4^{-q} \exp(-r/t_4) \quad , \qquad (10)$$

where the p, q and r values are given in Table 5 for the transitions of interest in the following discussion.

TABLE 5. COLLISIONAL RATES [a]

Transition	p (10^{-8})	q	r
2^3S, 3^3S	7.11	0.48	3.364
2^3S, 3^3P	5.25	0.38	3.698
2^3S, 3^3D	6.16	-0.22	3.776
2^3S, 3^1D	0.904	0.35	3.777
2^3S, 4^3S	3.26	0.41	4.378
2^3S, 4^3P	3.79	0.33	4.511
2^3S, 4^3D	3.65	-0.24	4.544
2^3S, 4^1F	0.276	0.47	4.544
2^3S, 4^3F	2.55	0.21	4.544

a. Parameters for the expressions $c = p\, t_4^{-q} \exp(-r/t_4)$ $cm^3\ s^{-1}$ (from the data by Berrington and Kingston 1987).

The ratio of the collisional excitation rate to the recombination rate of λ5876 is given by

$$\frac{I(5876)_C}{I(5876)_R} = N(2^3S)\, N_e \Big\{ [C(2^3S, 3^3D) + $$

$$+ C(2^3S, 4^3F)\, R(4^3F, 3^3D)]\, R(3^3D, 2^3P) \Big\} / N(He^+) N_e\, \alpha(5876)_{eff} \quad , \qquad (11)$$

where $\alpha(5876)_{eff}$ is the effective recombination coefficient and $R(3^3D, 2^3P)$ is the branching ratio given by

$$R(3^3D, 2^3P) = \frac{A(3^3D, 2^3P)}{A(3^3D, 2^3P) + A(3^3D, 3^3P)} \quad , \qquad (12)$$

and $R(4^3F, 2^3P)$ is given by a similar expression. From the A values by Weise *et al.* (1966), the $\alpha(5876)_{eff}$ value by Brocklehurst (1972) and the C values presented in Table 5 it follows that

$$\frac{I(5876)_C}{I(5876)_R} = \frac{7.27\, t_4^{0.39}\, e^{-3.776/t_4} + 3.01\, t_4^{-0.04}\, e^{-4.544/t_4}}{(1 + 3229\, t_4^{-0.24}\, N_e^{-1})} \quad , \qquad (13)$$

where the $C(2^3S, 4^3P)$ term that amounts to less than 3% of the total collisional value, was neglected.

Similarly for λ6678 it is found that

$$\frac{I(6678)_C}{I(6678)_R} = \frac{3.25\, t_4^{-0.16} e^{-3.777/t_4} + 0.99\, t_4^{-0.28} e^{-4.544/t_4}}{(1 + 3229\, t_4^{-0.24} N_e^{-1})} \quad , \qquad (14)$$

where we took into account the $C(2^3S, 3^1D)$ and the $C(2^3S, 4^1F)$ terms, while the $C(2^3S, 4^1P)$ term, that amounts to less than 1% of the total collisional value was neglected.

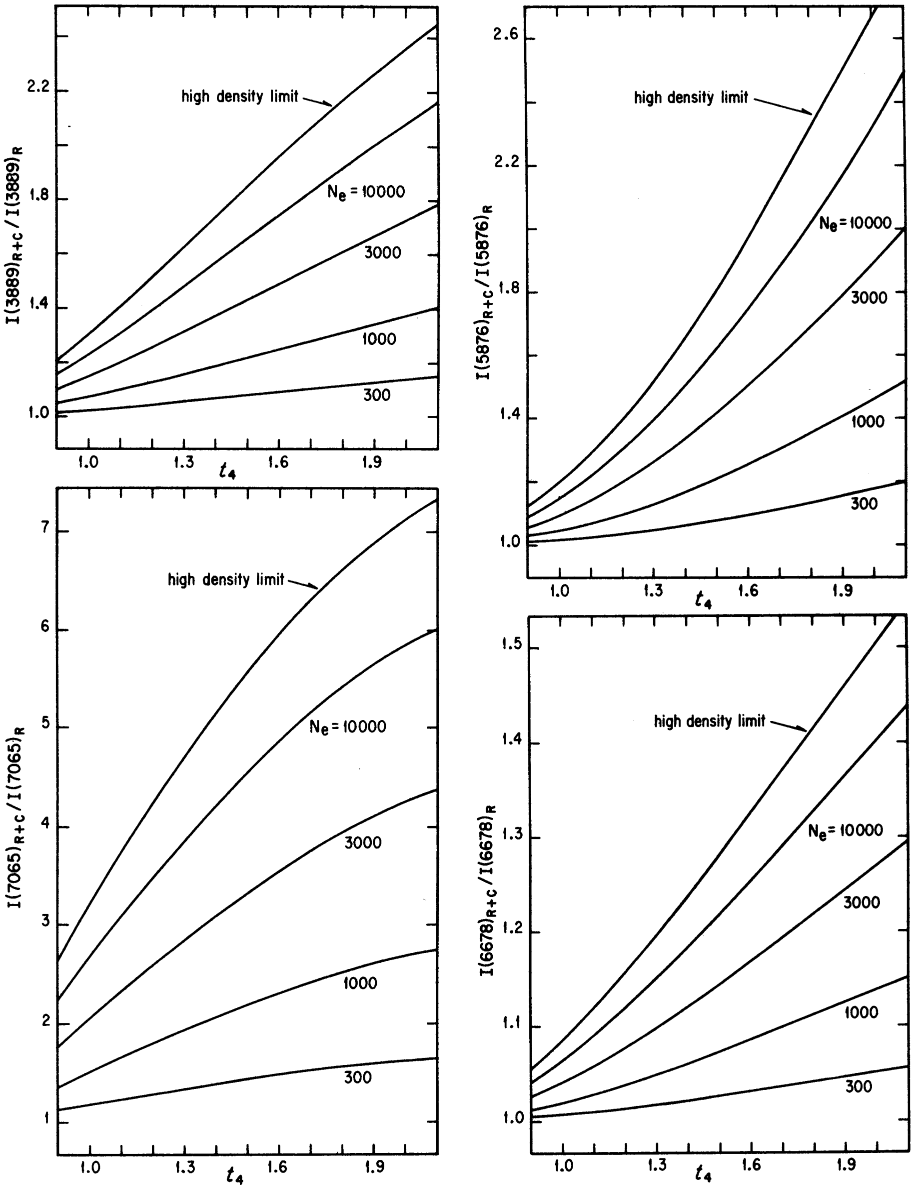

Fig. 2. Density and temperature dependence of the recombination plus collisional to recombination ratio for several He I line intensities.

For the λ4471 transition we only considered the $C(2^3S,\ 4^3D)$ term, the only one available, and obtained

$$\frac{I(4471)_C}{I(4471)_R} = \frac{12.25\ t_4^{\,0.32} e^{-4.544/t_4}}{(1 + 3229\ t_4^{-0.24}\ N_e^{-1})} \ . \qquad (15)$$

For the λ7065 transition we considered the $C(2^3S,\ 3^3S)$, $C(2^3S,\ 3^3P)$ and $C(2^3S,\ 4^3P)$ terms and neglected the $C(2^3S,\ 4^3S)$ and $C(2^3S,\ 4^3D)$ terms, that amounted to less than 2% and 1% respectively of the total collisional value, and obtained

$$\frac{I(7065)_C}{I(7065)_R} = (58.3\ t_4^{-0.94}\ e^{-3.364/t_4} + 4.39\ t_4^{-0.84} e^{-3.698/t_4} +$$

$$+ 2.92\ t_4^{-0.79} e^{-4.511/t_4})/(1 + 3229\ t_4^{-0.24} N_e^{-1}) \ . \qquad (16)$$

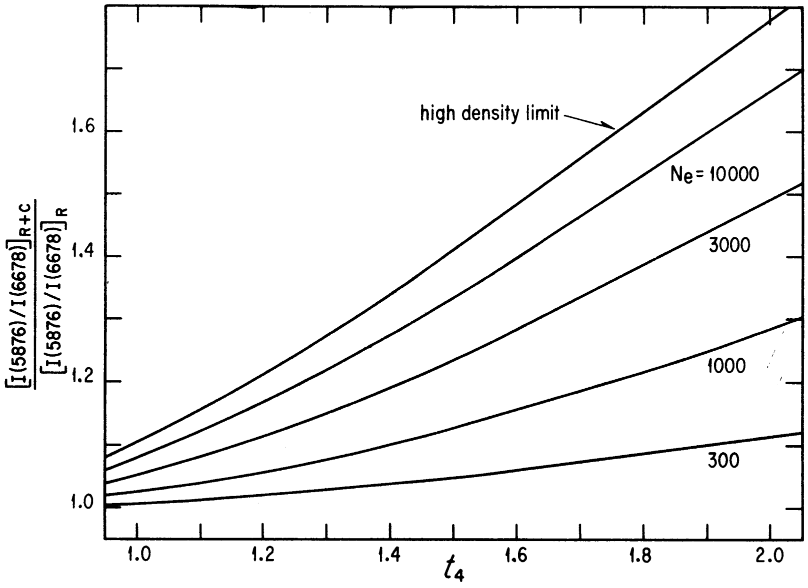

Fig. 3. Density and temperature dependence of the total I(5876)/I(6678) intensity ratio, collisional plus recombination terms, relative to the pure recombination case.

For the λ3889 transition we considered the $C(2^3S,\ 3^3P)$, $C(2^3S,\ 4^3S)$ and $C(2^3S,\ 4^3D)$ terms and neglected the $C(2^3S,\ 2^3D)$ term, that amounts to less than 1% of the total collisional value, and obtained

$$\frac{I(3889)_C}{I(3889)_R} = (10.17 t_4^{-0.61} e^{-3.698/t_4} + 2.41\ t_4^{-0.64} e^{-4.378/t_4} + $$
$$+ 1.49\ t_4^{\ 0.01} e^{-4.544/t_4})/(1 + 3229\ t_4^{-0.24} N_e^{-1}) . \qquad (17)$$

The expected effects of collisional excitation for the λλ5876, 6678, 7065 and 3889 lines as a function of T_e and N_e are presented in Figures 2 and 3 based on equations (13, 14, 16 and 17).

(*ii*) Optical Depth Effects in the Helium Singlets and Triplets.

Self-absorption from the 1^1S ground state might have a considerable effect on the emergent line intensities.

From the 5015/4471 and 5015/6678 observed ratios in Hu 1-2 and NGC 2440 (Aller and Walker 1970) together with the computations by Robbins and Bernat (1973) it is found that: $\tau(584) \sim 100$ for $v(R)/v(th) = 0$ or $\tau(584) \sim 300$ for $v(R)/v(th) = 3$. For these optical depths the effect of self-absorption on λ6678 is considerably smaller than 1% and it was not considered.

The absorption of line radiation by helium atoms in the metastable 2^3S state affects the line intensities of the helium triplets producing a sharp decrease in the line intensities of the principal series, like λ3889 and λ3188, while lines of other series, like λ7065 and λ4713, will be enhanced considerably. Fortunately the triplet lines that will be used to estimate the $N(He^+)/N(H^+)$ abundances, those of λ4471 and λ5876 depend weakly on the optical depth. We will estimate the optical depth at $\tau(3889)$ by comparing the λ3889 and λ7065 line intensities which are strongly affected by optical depth effects.

In the presence of self-absorption, to a very good approximation, the increase in the λ(7065) line intensity is due to a decrease in the λ(3889) line intensity; by a linear combination of these two line intensities and from the computations by Robbins (1968*a*) it is possible to obtain a value for the helium abundance independent of the optical depth, the expression is

$$y^+(3889,7065) = 0.24\ y^+(7065) + 0.76\ y^+(3889), \qquad (18)$$

where

$$y^{+}(\lambda) = N(He^{+},\lambda)/N(H^{+}). \tag{19}$$

(*iii*) Helium Abundances.

In Table 6 we present the derived values of the helium abundance without corrections from the collisional and self-absorption effects. In all objects I(7065) is considerably larger than recombination theory predicts and yields abundance values considerably higher than tha other four lines implying that collisional and/or self-absorption effects are affecting its intensity.

In Table 7 we present the helium abundances of the four objects with highest N_e and T_e, including three different positions for Hu 1-2, for which the collisional effects are more important. We estimated the collisional effects from the $T_e(O^{+++})$ and the N_e (adopted) values presented in Table 4. In Table 7 we are assuming that the population of the 2^3S level is given by equation (9) and that the collisional terms are those given in Table 5, furthermore, the self-absorption effects are not considered.

TABLE 6. HE^{+} ABUNDANCE WITHOUT CORRECTIONS [a]

Object	$y^{+}(3889)$[b]	$y^{+}(4471)$	$y^{+}(5876)$	$y^{+}(6678)$[c]	$y^{+}(7065)$	Notes
NGC 650-1	0.1025	0.0910	0.1021	0.0869	0.1546	...
NGC 2346	0.0888	0.1093	0.1067	0.0996	...	...
NGC 2371-2	0.0479	0.0380	0.0390	0.0390	0.0563	...
NGC 2440*a*	0.0573	0.0559	0.0628	0.0613	0.1729	d
NGC 2440*b*	0.1027	0.0895	0.1051	0.1051	...	...
NGC 2818	0.0925	0.0946	0.1137:	...	...	...
NGC 7293	<0.1122:	0.1288:	0.1413:	...	...	...
Hu 1-2*a*	0.0834	0.0727	0.0874	0.0727	0.2579	d
Hu 1-2*b*	0.0815	0.0744	0.0834	0.0760	0.2762	d
Hu 1-2*c*	0.0580	0.0666	0.0698	0.0593	0.2155	d
M 1-8	...	0.0940	0.1079	...	...	...
M 1-13	0.0964:	0.1132	0.1082	0.0920	0.2013	...
M 1-17	0.0651	0.1104	0.1130	0.1054	0.3829	d
M 2-55	0.0994	0.1195	0.1065	...	...	...
M 3-3	0.1018:	0.1066	0.0994	0.0827	...	...
Me 2-2	0.0692	0.1622	0.1778	0.1698	0.9551	d
<Mean of 6>	...	0.0904	0.0990	0.0907	...	...

a. The He^{+} contribution to $H\beta$ has been taken into account.
b. The $H8$ and He^{+} contribution have been taken into account.
c. The He^{+} contribution to 6678 has been taken into account.
d. These objects have a significant collisional effect, they have been included in the "mean of 6".

As can be seen from Table 7, $y^{+}(6678)$ is systematically higher than $y^{+}(5876)$ and $y^{+}(4471)$; by including the self-absorption effects the difference would be even larger. For example, to reach agreement between $y^{+}(6678)$ and $y^{+}(5876)$ for Hu 1-2 the collisional effects require (see Table 6 and Fig. 3): a) T_e(O III) values of ∿ 13 000 K, which is ruled out by the observations (T_e(O III) = 18 500 - 19 000 K); or b) N_e values of ∿ 1000 cm^{-3} which is also ruled out by the observations (N_e ∿ 5000 cm^{-3}). Another possibility is that the C terms in Table 5 have been overestimated by about a factor of four which is also unlikely. A similar situation prevails for the other 3 objects.

It seems that the depopulation of the 2^3S state is probably not completely understood. In what follows we will assume that the $N(2^3S)$ population is only a fraction of that predicted by equation (9) and that it is given by

$$\frac{N(2^3S)}{N(He^{+})} = \frac{\gamma\ 5.82\times10^{-6}t_4^{-0.97}}{(1 + 3229\ t_4^{-0.24}N_e^{-1})}, \tag{20}$$

consequently we will try to determine the parameter γ for each object.

TABLE 7. HE^+ ABUNDANCE WITH FULL COLLISIONAL CORRECTION

Object	y^+(3889)	y^+(4471)	y^+(5876)	y^+(6678)	y^+(7065)
NGC 2440*a*	0.0379	0.0397	0.0418	0.0522	0.0457
Hu 1-2*a*	0.0449	0.0372	0.0424	0.0549	0.0523
Hu 1-2*b*	0.0460	0.0413	0.0436	0.0591	0.0594
Hu 1-2c	0.0346	0.0395	0.0388	0.0475	0.0513
M 1-17	0.0512	0.0965	0.0939	0.0975	0.1373
Me 2-2	0.0486	0.1316	0.1341	0.1504	0.2539
<Mean of 6>	...	0.0643	0.0657	0.0769	...

Since y^+(6678) is less affected by collisional effects than the other lines, it is possible, in the absence of observational errors, to determine γ from the intersection of y^+(6678) with another y^+ function, for example y^+(5876) and y^+(3889,7065) in the y^+, γ diagram. For NGC 2440*a* and Hu 1-2 we made use of the y^+(5876) and y^+(3889,7065) intersections with y^+(6678) while for M 1-17 and Me 2-2 we only used the last one.

In Table 8 we present the γ values derived with the procedure mentioned above. Also in this table we present the y values corresponding to those γ without correcting for self-absorption. For the other objects it is not possible from our observations to determine a value of γ since the collisional effects are comparable or smaller than the observational errors. By including self-absorption the γ values derived from y^+(5876) become slightly smaller.

TABLE 8. HE^+ ABUNDANCE WITH PARTIAL COLLISIONAL CORRECTION

Object	y^+(3889)	y^+(4471)	y^+(5876)	y^+(6678)	y^+(7065)	γ
NGC 2440*a*	0.0520	0.0509	0.0507	0.0559	0.1026	0.25±0.15
Hu 1-2*a*	0.0603	0.0510	0.0592	0.0635	0.0937	0.45±0.20
Hu 1-2*b*	0.0643	0.0581	0.0633	0.0691	0.1220	0.35±0.20
Hu 1-2c	0.0446	0.0507	0.0514	0.0533	0.0887	0.45±0.20
M 1-17	0.0602	0.1058	0.1065	0.1029	0.2492	0.30±0.20
Me 2-2	0.0592	0.1484	0.1573	0.1615	0.4538	0.40±0.20
<Mean of 6>	...	0.0775	0.0814	0.0844	...	0.37

It is also possible that the presence of dust inside the PN affects the helium line intensities. For high values of τ_0(3889) and under the presence of dust I(3889) decreases without increasing I(7065). Therefore if dust is present inside the nebula the y^+(3889,7065), y^+(6678) intersection takes place at a lower value of γ than the real one. Since in general the γ values derived from y^+(5876) are smaller than those derived from y^+(3889,7065) we consider this effect to be very small and it has not been included in the derivation of γ (see also the discussion on λ10830 later on).

From the observations by O'Dell (1963) of the I(10830)/I(5876) ratio in 9 PN, several authors found that I(10830) was too weak by factors of 2.5 to 5 if only the D_A and D_C terms in equation (7) were included (see Robbins 1968*a*; Persson 1970, and references therein). The possiblity that internal dust was responsible for the weakness of I(10830) in gaseous nebulae was advanced by Robbins (1970) and Persson (1970).

Persson (1972) presented observations for 27 PN of $\lambda\lambda$5876, 7065 and 10830, he assumed that the discrepancy between the theoretical and the observed I(10830)/I(5876) ratios was mostly due to internal dust absorption. The dust optical depth at λ10830 along the radius of the nebula, τ_0(10830), was in many cases considerably larger than the corresponding one from the total C(Hβ) value derived from the Balmer decrement or from comparing F(Hβ) with radio observations. Since the C(Hβ) values are mainly produced by material between the PN and the observer, we conclude that even if dust is present in PN it is not the primary cause for the low I(10830)/I(5876) ratios and that there is an efficient mechanism, additional to D_A and D_C, responsible for depopulating the 2^3S level.

From the results by Persson (1972) the effect on I(10830) due to dust absorption is considerably higher than on I(7065). The decrease of I(7065) is of a factor in the 1.01 to 1.10 range, even in the extreme case in which all the difference between the observed and the theoretical I(10830)/I(5876) ratio is explained by the dust presence. Therefore even in the presence of the maximum amount of dust allowed by the I(10830)/I(5876) ratio the γ value determined by us from the $y^+(3889,7065)$, $y^+(6678)$ intersection will not increase by more than 0.05.

From: a) observations of the I(10830)/I(6678) ratio in NGC 6572, NGC 6803, NGC 7027 and IC 418, b) the He I collisional computations (Berrington *et al.* 1985; Berrington and Kingston 1987), c) the radiative transfer work by Robbins (1968*a*), d) The He I recombination coefficients by Brocklehurst (1972), e) partial collisional effects as given by equation (20), and f) assuming that dust destruction of λ10830 photons is negligible, we find values of γ in the 0.5 to 0.8 range (Peimbert and Torres-Peimbert 1987). These values are larger than those presented in Table 8 and imply that if the γ values derived from the observations presented in this paper are correct, then dust destruction is not the primary cause for the relative weakness of the I(10830)/I(5876) ratio.

From the values presented in Table 8 and the results derived from the I(10830)/I(5876) line intensity ratio it follows that $\gamma \sim 0.5 \pm 0.2$ is a representative value for PN. The variations of γ from object to object might be real, but higher quality observations are needed to establish this point.

In Table 9 we present the He abundances for all the observed PN by adopting a $\gamma = 0.5$ for all objects after correcting for the collisional contribution and the self-absorption effects.

Also in Table 9 we present the $\tau_0(3889)$ values under the assumption that v(R)/v(th) = 3; for v(R)/v(th) = 0 the $\tau_0(3889)$ values decrease by about a factor of 2 (Robbins 1968*a*). The $\tau_0(3889)$ values were mainly derived from the I(7065)/I(3889) ratios. To correct the $y^+(5876)$ and $y^+(4471)$ values for self-absorption we have used the results by Robbins (1968*a*) normalized to the maximum values for total self-absorption presented by Cox and Daltabuit (1971) which are based on more recent transition probabilities than those used by Robbins.

The self-absorption effect is almost negligible for $y^+(4471)$ and $y^+(5876)$ since on the average it amounts to about 0.3% and 1% respectively. In Tables 8 and 9 for the mean of six

TABLE 9. HE^+ ABUNDANCES WITH SELF-ABSORPTION CORRECTION AND PARTIAL COLLISIONAL CORRECTION ($\gamma = 0.50$)

Object	$\tau_0(3889)^{a,b}$	$y^+(4471)$	$y^+(5876)$	$y^+(6678)$
NGC 650-1	1.3	0.0877	0.0970	0.0852
NGC 2346	5.9	0.1067	0.1033	0.0984
NGC 2371-2	1.0	0.0368	0.0374	0.0384
NGC 2440*a*	4.1	0.0463	0.0499	0.0564[c]
NGC 2440*b*	0.6	0.0808	0.0924	0.1002
NGC 2818	4.0	0.0899	0.1075:	...
NGC 7293	5.9	0.1282:	0.1398:	...
Hu 1-2*a*	1.8	0.0492	0.0569	0.0624[c]
Hu 1-2*b*	4.0	0.0530	0.0559	0.0665[c]
Hu 1-2*c*	6.3	0.0492	0.0493	0.0527[c]
M 1-8	(10.0)[d]	0.0918	0.1037	...
M 1-13	4.3	0.1287	0.1018	0.0899
M 1-17	16.2	0.1024	0.1005	0.1013[c]
M 2-55	4.2	0.1182	0.1046	...
M 3-3	(4.0)[d]	0.1050	0.0972	0.0821
Me 2-2	30.7	0.1432	0.1477	0.1595[c]
<Mean of 6>	...	0.0739	0.0767	0.0831
<Mean of 12>	...	0.0824	0.0824	0.0828

a. Optical depth for v(R)/v(th) = 3, from Robbins (1968*a*).
b. Typical errors in the optical depth are ±2.0.
c. Objects in the mean of 6.
d. Numbers in parenthesis are adopted values.

$< y^+(6678) >$ is higher than $< y^+(5876) >$, agreement could be reached by lowering γ to about 0.25; on the other hand $< y^+(6678) >$ agrees with $< y^+(3889, 7065) >$ for $\gamma \sim 0.50$. It is possible that the differences in the values of γ derived from the various helium lines are due to observational errors. We do not think that I(6678) has been systematically overestimated since for the mean of twelve, made with all the objects with measured I(6678), $< y^+(6678) > \sim < y^+(5876) > \sim < y^+(4471) >$.

The total helium abundance is given by

$$\frac{N(He)}{N(H)} = \frac{N(He^\circ + He^+ + He^{++})}{N(H^\circ + H^+)} , \qquad (21)$$

for objects of low degree of ionization there is an outer He° zone within the H^+ zone, alternatively for objects of high degree of ionization there is an outer H° zone within the He^+ zone and no He° zone. If one is dealing with a density bounded nebula the He° and H° zones can disappear. We did not consider the He° and H° terms in equation (21) for the objects presented in this paper.

In Table 10 we present the total He abundances. The He^+/H^+ abundances were obtained by giving weights of 2, 1 and 1 to $y^+(5876)$, $y^+(6678)$ and $y^+(4471)$ respectively. In all the abundances relative to H^+ we have considered the contribution of the lines of the Pickering series to the Balmer lines based on the observed strength of λ4686 and the computations by Hummer and Storey (1987); the Balmer line intensities in Tables 2 and 3 correspond to the observed intensities and include the Pickering line intensities. The $N(He^{++})/N(H^+)$ ratio was derived from the I(4686)/I(4861) line intensity ratio and the computations by Hummer and Storey (1987). By considering only the errors due to the line intensity determinations we estimate that the one standard deviation errors are smaller than a factor of 1.05 in the $N(He^+ + He^{++})/N(H^+)$ ratios.

TABLE 10. HELIUM ABUNDANCE[a]

Object	He^+	He^{++}	He
NGC 650-1[b]	0.092	0.035	0.127
NGC 2346	0.103	0.033	0.136
NGC 2371-2	0.038	0.081	0.119
NGC 2440*a*	0.051	0.072	0.123
NGC 2440*b*	0.092	0.046	0.138
NGC 2818[c]	0.098	0.066	0.164
NGC 7293	0.136	<0.002	0.136
Hu 1-2*a*	0.056	0.089	0.145
Hu 1-2*b*	0.058	0.089	0.147
Hu 1-2*c*	0.050	0.099	0.149
M 1-8	0.100	0.052	0.152
M 1-13	0.106	0.015	0.121
M 1-17[b]	0.101	0.012	0.113
M 2-55	0.109	0.028	0.137
M 3-3	0.095	0.030	0.125
Me 2-2	0.150	0.000	0.150

a. Given in $N(He^i)/N(H^+)$.
b. Probably have a considerable amount of He° inside the H^+ zone.
c. For this object we gave equal weight to I(4471) and I(5876).

Of the PN presented in Table 10 NGC 650-1 has the highest $N(S^+)/N(S)$ ratio probably indicating the presence of a significant amount of He° inside the H^+ zone; if it is assumed that $N(He^\circ)/N(He) = N(S^+)/N(S)$ then N(He)/N(H) would be increased to 0.149.

c) Other Elements.

The ionic chemical abundances were derived adopting a two temperature scheme: for the N^+, O^+, S^+ and S^{++} ions we used T_e(N II) while for all the other ions we used T_e(O III). For all ions we used the adopted densities presented in Table 4.

From the data reported in this paper, it is not possible to determine abundances for all the ions present of a given element, therefore to obtain the total abundances we have to make use of ionization correction factors or we have to neglect some ionic species. The total abundances were obtained from

$$\frac{N(O)}{N(H)} = \frac{N(He^{+} + He^{++})}{N(He^{+})} \frac{N(O^{+} + O^{++})}{N(H^{+})} , \tag{22}$$

$$\frac{N(N)}{N(H)} = \frac{N(O)}{N(H)} \frac{N(N^{+})}{N(O^{+})} , \tag{23}$$

$$\frac{N(Ne)}{N(H)} = \frac{N(O)}{N(H)} \frac{N(Ne^{++})}{N(O^{++})} , \tag{24}$$

$$\frac{N(Ar)}{N(H)} = \frac{N(Ar^{++} + Ar^{3+} + Ar^{4+})}{N(H^{+})} , \tag{25}$$

and are presented in Table 12.

TABLE 11. IONIC ABUNDANCES[a]

Object	C^{++} 4267	N^{+} 6584	O^{+} 3727	O^{++} 5007	Ne^{++} 3869	Ne^{3+} 4725	S^{+} 6724	S^{++b} 6311	Cl^{++} 5527	Ar^{++} 7136	Ar^{3+} 4740	Ar^{4+} 7006
NGC 650-1	-3.03:	-3.95	-3.56	-3.61	-4.05	-4.98::	-5.49	-5.07	-6.96	-5.69	-6.97	...
NGC 2346	-3.00::	-4.14	-3.68	-3.57	-4.04	-4.14::	-6.71	-5.28	...	...	-6.66	...
NGC 2371-2	-3.12	-4.82	-4.42	-3.79	-4.44	-4.35	-6.24	-5.00	-7.17	-5.94	-5.93	-6.39
NGC 2440*a*	-3.26	-4.07	-4.24	-3.86	-4.56	-4.76	-6.22	-5.47	-7.43:	-6.01	-6.16	-6.40
NGC 2440*b*	-3.31:	-3.65	-3.83	-3.77	-4.37	-4.71	-5.86	-5.15	-7.27:	...	-6.30	...
NGC 2818	-3.30	-4.26	-4.18	-3.88	-4.37	-5.00	-5.94	-5.00	...	...	-6.52	...
NGC 7293	...	-3.64	-3.24	-3.79	-4.06	...	-6.16	...	...	-5.58	...	...
Hu 1-2*a*	-3.65	-4.78	-4.84	-4.35	-4.96	-5.31	-6.47	-5.61	...	-6.54	-6.55	-6.77
Hu 1-2*b*	...	-4.82	-4.86	-4.28	-4.93	-5.21	-6.52	-5.63	...	-6.47	-6.48	-6.79
Hu 1-2*c*	...	-4.88	-5.03	-4.33	-5.04	...	-6.58	-5.58	...	-6.46	-6.42	-6.70
M 1-8	-2.91	-4.51	-4.27	-3.69	-4.23	...	-6.61	-5.71	...	...	-6.38	...
M 1-13	...	-4.20	-3.84	-3.53	-4.09:	...	-6.21	...	-7.09:	-5.80	-6.55	...
M 1-17	-3.04	-4.51	-4.21:	-3.47	-4.17:	...	-5.87	-5.41	-7.05	-5.88:	-6.37	-7.29:
M 2-55	...	-4.34	-3.96	-3.55	-3.99	...	-6.10	...	...	-5.64:	...	-5.99:
M 3-3	-3.02::	-3.80	-4.04	-3.75	-4.25	...	-6.75	...	...	...	...	...
Me 2-2	-3.06	-4.42	-4.23	-3.78	-4.39	-5.35::	-6.72	-5.97	...	-6.15	-7.32	...

a. Given in log $N(X^{i})/N(H^{+})$.

b. I(6310) of He^{+} has been taken into account.

TABLE 12. TOTAL ABUNDANCES[a]

Object	N(N)	N(O)	N(Ne)	N(Ar)
NGC 650-1	8.51	8.86	8.42	...
NGC 2346	8.34	8.80	8.33	...
NGC 2371-2	8.41	8.80	8.15	...
NGC 2440*a*	8.98	8.65	7.95	6.32
NGC 2440*b*	8.92	8.67	8.07	...
NGC 2818	8.43	8.51	8.02[b]	...
NGC 7293	8.49	8.89	8.62	...
Hu 1-2*a*	8.32	8.19	7.58	5.87
Hu 1-2*b*	8.30	8.20	7.56	5.86
Hu 1-2*c*	8.40	8.21	7.50	5.97
M 1-8	8.34	8.59	8.05	...
M 1-13	8.52	8.82	8.26	...
M 1-17	8.36	8.65	7.95	...
M 2-55	8.31	8.69	8.25	...
M 3-3	8.79	8.55	8.05	...
Me 2-2	8.13	8.35	7.74	...

a. Given in 12 + log N(X)/N(H).

b. This value is an upper limit, see text.

Equations 22 to 25 yield accurate abundances for most objects but not for all, for example: a) for PN of low degree of ionization and at large distances from the ionizing star equation (24) overestimates the abundance of Ne, and b) for objects of low degree of ionization the $N(Ar^+)/N(H^+)$ term becomes important and should be included in equation (25), for this reason we only included the Ar abundance of the objects with the highest degree of ionization. To obtain more accurate abundances the UV and IR observations as well as models of each object have to be included, these actions are beyond the scope of this paper. Nevertheless we will give a preliminary discussion on the abundances in Tables 11 and 12.

The C^{++} abundances determined from the permitted C II 4f-3d λ4267 line based on hydrogenic recombination theory (Pengelly 1963) are often higher than the C^{++} abundances determined from the C III] 1909 line which is produced by collisional excitation; while for the Orion nebula, IC 418 and NGC 40 both methods yield similar results (Torres-Peimbert *et al.* 1980; Clegg *et al.* 1983), for other objects differences up to an order of magnitude have been found (e.g. Barker 1982). In a recent paper where Kaler (1986) discusses this problem based on observations of thirty objects he suggests that the λ4267 abundances should be reduced by a factor of four to reach agreement between the abundances derived from both methods; no physical explanation for this proposed reduction has yet been found.

The $N(C^{++},4267)$ abundance derived in this paper for NGC 2818 is seven times higher than the $N(C^{++}, 1909)$ abundance derived by Dufour (1984). We do not have an explanation for this difference, nevertheless we would like to note that in the presence of temperature variations over the observed volume, due to density fluctuations or to chemical inhomogeneous regions (for example C and He rich), the $N(C^{++}, 1909)$ abundance would become a lower limit to the real one while the $N(C^{++}, 4267)$ abundance would remain unaffected.

French (1983) based on C abundances derived from recombination lines has found that C^{++} is the dominant ionization stage over a wide range of ionization levels and has suggested that $N(C)/N(O) = 1.25\ N(C^{++})/N(O)$ is a good relation that provides abundances that are accurate to better than 50%. Alternatively Harrington *et al.* (1982) based on models for NGC 7662, a PN of relatively high degree of ionization, have found that $N(C)/N(O) \approx 2\ N(C^{++})/N(O)$. In any case even if $N(C)/N(O) = N(C^{++})/N(O)$ from the $N(C^{++}, 4267)$ abundances presented in Table 11 it follows that all the objects studied in this paper have N(C)/N(O) ratios larger than unity.

The N(Ne)/N(O) ratio in NGC 7293 is higher than in other PN in agreement with the results of Hawley (1978). Equation (23) breaks down at the edge of extended objects of low degree of ionization where the Ne^{++} region coincides with the O^+ region (Hawley and Miller 1977, 1978; Hawley 1978), therefore the Ne/O ratio for NGC 7293 presented in Table 12 is unreliable and corresponds to an upper limit.

From Tables 10 and 12 it follows that the objects presented in this paper are He and N rich and therefore that they belong to the Type I category. Type I PN seem to originate from progenitors who had from 2 to 8 $M_\odot$ in the main sequence. Comparisons of the observed abundances with theoretical predictions from stellar evolution models of intermediate mass stars have been presented elsewhere (e.g. Renzini and Voli 1981; Shields *et al.* 1981, Iben and Renzini 1983; Dufour 1984; Torres-Peimbert 1984; Renzini 1984; Peimbert 1984, 1985; Clegg 1985).

IV. DISCUSSION AND CONCLUSIONS

From the comparison between the theoretical and observed [O III], [N II] and 4451/4686 ratios it was found that the IIDS detectors are non-linear and that $\beta = 0.07 \pm 0.01$. After correcting for this non-linearity the observations repeat very well and accuracies as high as 0.02 dex in line intensity ratios can be achieved. It is suggested that the line intensity ratios mentioned above should be observed with the different detectors in use to establish their characteristics not only in the laboratory but at the telescope, under ordinary conditions of operation.

We have presented line intensities for thirteen N-rich PN. From these line intensities we have determined the collisional effects in the helium line intensities and the chemical abundances of the most abundant elements.

The results by Berrington and Kingston (1987) are very similar to those by Berrington *et al.* (1985) for transitions from the 2^3S state to states with n = 1 and n = 2 but not so for transitions to states with n = 3. The new results show that the main terms for the collisional contribution to I(5876) and I(6678), $C(2^3S, 3^3D)$ and $C(2^3S, 3^1D)$, are 1.5 to 1.7 times smaller, in the $1 \leq t_4 \leq 2$ range, than the previous values. Therefore the determination of N(He)/N(H) abundance ratios derived from these lines are correspondingly less affected by collisional efefects.

Pequignot *et al.* (1987) by comparing He line observations of NGC 7027 with a theoretical model have found that the $C(2^3S,3^3D)$ and $C(2^3S, 3^1D)$values are about a factor of 1.85± 0.35 smaller and a factor of 1.14±0.4 larger than the values given by Berrington *et al.* (1985).

We were able to determine accurate y^+ values from the λλ6678, 5876, 4471, 3889 and 7065 lines of helium; to be able to reconcile the abundances derived from the different lines, if we considered only the D_A and D_C terms in equation (7) we had to assume that the collisional effects were about a factor of two smaller than predicted by Berrington and Kingston (1987). There are several possibilities to explain this difference, one of them is to assume that there is an efficient mechanism that depopulates the $N(2^3S)$ level that has not been properly considered. We defined a parameter γ which gives us the fraction of depopulations from the 2^3S level due to D_A and D_C. From our observations we found values of γ in the 0.25 to 0.50 range. The difference between γ and 1 could be due to ionizations from the 2^3S level, terms $D_i(Ly\,\alpha)$, D_i(stellar), D_i(coll.) and D_e in equation (7).

From observations of I(10830) in other PN, not reported here, we found values of γ in the 0.5 to 0.8 range, under the assumption that dust is not destroying λ10830 photons inside those nebulae.

By considering the γ values obtained in this paper with those obtained from the λ10830 line intensities we adopted a value of $\gamma = 0.50$ for all the objects to determine the He/H abundance ratios. It is found that the group of N-rich PN is also helium rich. The maximum reduction in the total He/H ratio due to collisional effects is for Hu 1-2 which decreases from 0.168 to 0.148, for all the other objects the reduction is considerably smaller (see Tables 6 and 10).

To derive accurate values of γ we suggest that the helium lines λλ3889, 4471, 5876, 6678, 7065 and 10830 should be observed in Hu 1-2, NGC 2440, NGC 7027 and PN of Type I in the Magellanic Clouds, where we expect large collisional effects.

So far the best galactic PN known to study the collisional effects is Hu 1-2 which shows the highest T_e value with a reasonably high N_e value. Moreover Hu 1-2 might be more comparable to PN in the Magellanic Clouds and to metal poor extragalactic H II regions due to its relatively low O/H ratio and to its apparently small dust to gas ratio. In the diagram M_{dust}/M_{gas} versus radius Hu 1-2 is about a factor of four below the galactic PN mean relation indicating that probably is dust deffícient (Pottasch *et al.* 1984).

Due to their low O/H ratio we expect the PN in the Magellanic Clouds to have high T_e values, even more so those that are of Type I which are in general ionized by hotter stars than the other types of PN (e.g. Peimbert 1984 and references therein).

Ferland (1986) has determined the pregalactic helium abundance, Yp, from six independent He/H determinations of five different oxygen-poor extragalactic H II regions, he finds that without considering collisional effects $\langle Yp \rangle = 0.227$ and by considering collisional effects $\langle Yp \rangle = 0.207$.

Pagel (1987) and Shields (1987) have suggested that Ferland (1986) overestimated the electron densities, and therefore the collisional effects, by about a factor of three. Consequently the pregalactic abundance by Ferland should be increased to Yp = 0.220.

If we combine the 1.6 factor reduction from the new collisional values by Berrington and Kingston (1987) with a value of $\gamma = 0.5$ from our results we would have to reduce further the collisional effects by another factor of about three. Therefore the Yp value by Ferland (1986) would have to be raised to Yp = 0.225. The difference between the pure recombination case and that corrected by collisions becomes almost negligible.

Moreover if ionizations are responsible for the low value of γ, there is at least one factor that makes us expect a higher rate of ionizations from the 2^3S level in heavy element poor extragalactic H II regions than in galactic PN: the considerably larger stellar flux in the 912 A to 2600 A range, due to B and A stars of different luminosities, able to ionize He atoms from the 2^3S level; see for example the spectra of I Zw 18, NGC 2366, NGC 4861 and NGC 5471 in the IUE atlas by Rosa *et al.* (1984).

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