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IONIZATION STRUCTURE OF GASEOUS NEBULAE: SULPHUR, NITROGEN AND HELIUM

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RESUMEN

Se presentan modelos detallados de la estructura de ionización de nebulosas gaseosas para diferentes densidades electrónicas y diferentes campos de radiación. Se analizan diversas posibilidades para explicar las observaciones de los cocientes de intensidades [S II]/[N II] en la Nebulosa de Orión, ya que los cocientes observados son mayores que las predicciones a partir de nuestros modelos.

Se encuentra que la estructura de ionización de los elementos pesados depende considerablemente de la densidad electrónica. También se encuentra que la cantidad de helio neutro en una región H II se puede derivar observacionalmente una vez obtenido el grado de ionización de los elementos pesados si además se conoce la densidad electrónica.

ABSTRACT

Detailed ionization structure models of gaseous nebulae, for different electron densities and ionizing radiation fields are presented. The observed [S II]/[N II] line intensity ratios in the Orion Nebula are greater than those predicted by our models. Possible explanations for this discrepancy are analyzed.

It is found that the ionization structure of the heavy elements critically depends on the electron density. From the computations it follows that in order to infer by observation the amount of neutral helium in a given H II region, it is necessary that not only the degree of ionization of heavy elements should be obtained, but also that its electron density should be known.

Key words: ABUNDANCES, NEBULAR — FORBIDDEN LINES — GALACTIC NUCLEI — NEBULAE.

I. INTRODUCTION

This is the first paper of a series based on a general ionization structure program that we are developing to study the physical conditions in gaseous nebulae. In this paper we are interested in the very large [S II] line intensities observed in gaseous nebulae, in the constancy of the sulphur to nitrogen ratio I(6717 + 6731)/I(6584), found by Benvenuti, D'Odorico and Peimbert (1973) in the H II regions close to the nucleus of M33, and in the presence of neutral helium in the regions where presumably the [S II] emission originates. In § II we describe the ionization structure program. In § III we discuss the inclusion of charge exchange reactions in our models; in particular, the reactions $S^{++}(^3P) + He^0 \rightarrow He^+ + S^+$ and $S^{++}(^1D) + He^0 \rightarrow He^+ + S^+$ are analyzed. In § IV we show the ionization structure of models, for several stellar temperatures and electron densities. A brief comparison of these models, with observations, is presented in § V and the conclusions are presented in § VI.

II. FORMULATION OF THE PROBLEM

To derive the ionization structure of a spherical nebula excited by a central star we have followed

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very closely the formulation of the problem by Hummer and Seaton (1963, 1964) and Flower (1969).

In particular we have made the following assumptions: *a*) We have considered the diffuse radiation to be reabsorbed "on the spot". Details will be given below. *b*) Since we are considering stars with effective temperatures in the range 30 000 to 35 000°K we have not included He^{+2}. *c*) We assumed a uniform temperature throughout the nebula. This does not critically affect the results since the recombination coefficients depend only slightly on the electron temperature. *d*) The transfer equation was solved together with the ionization equilibrium equations for H and He. From the derived ionization structure of H and He we obtained the radiation field and electron density as a function of nebular radius, and from these, the ionization structure of the heavy elements was derived.

We used the approximation

$$J_\nu = J_\nu^{(s)} + J_\nu^{(d)} \qquad (1)$$

where $J_\nu = \frac{1}{4\pi}\int I_\nu d\omega$ is the mean photon intensity, I_ν is the photon intensity (I_ν in photons cm^{-2} s^{-1} hz^{-1} sr^{-1}), and the super-scripts (s) and (d) refer to stellar and diffuse components, respectively.

The mean stellar photon intensity at radius r is given by the transfer equation

$$4\pi J_\nu^{(s)} r^2 = \pi F_\nu r_*^2 \exp(-\tau_\nu), \qquad (2)$$

where πF_ν is the flux emerging from the stellar atmosphere (πF_ν in photons cm^{-2} s^{-1} hz^{-1}), r_* is the stellar radius, and

$$d\tau_\nu = \kappa_\nu dr. \qquad (3)$$

The opacity (κ_ν in cm^{-1}) is given by

$$\kappa_\nu = N(H^0)\, a_\nu(H^0) + N(He^0)\, a_\nu(He^0), \qquad (4)$$

where $N(H^0)$ and $N(He^0)$ are the neutral hydrogen and helium number densities, respectively; and a_ν is the ionization cross section from the ground state.

For the diffuse radiation we have adopted

$$J_\nu^{(d)} = \frac{j_\nu}{\kappa_\nu} \qquad (5)$$

where j_ν is the photon emissivity due to recombination processes within the nebula (j_ν in photons cm^{-3} s^{-1} hz^{-1} sr^{-1}). The ionization equilibrium equation for the elements considered can be written, for the case of negligible collisional ionization, as

$$N(X^{+m}) \int_{\nu_0}^{\infty} 4\pi J_\nu a_\nu(X^{+m})\, d\nu = N_e N(X^{+m+1}) \times \alpha(X^{+m},T_e)\,; \qquad (6)$$

where $\alpha(X^{+m},T_e)$ is the total recombination coefficient for the electron temperature T_e (α in cm^3 s^{-1}). The recombination coefficient is defined by

$$\alpha(X^{+m},T_e) = \sum_{n=1}^{\infty} \alpha_n = \sum_{n=1}^{\infty} \int_{\nu_n}^{\infty} \alpha_{n,\nu} d\nu$$

where α_n is the coefficient for recombination to level n, and ν_n is the corresponding threshold frequency. The electron density is considered to be given by

$$N_e = N(H^+) + N(He^+). \qquad (7)$$

To simplify the program we treated the diffuse radiation by assuming that H^0 and He^0 reabsorbed "on the spot" their own Lyman continua. We also neglected the effects of He I Lyman-α and two-quantum emission. This approximate treatment seems to be well justified for H II regions in which no He^{+2} is present and N(He)/N(H) does not take a very large value (Rodríguez, Torres-Peimbert and Peimbert 1974).

We also assumed that photoionization of heavy elements was due only to stellar radiation. In almost the entire nebula the heavy elements are present, at each point, predominantly at one, or at most two, stages of ionization. Stellar radiation dominates the proportion between the more abundant upper ionization stages; while diffuse radiation, because of its characteristics of lower energy, tends to make its presence felt in the relative proportion of the less abundant, lower ionization stages. As one is usually concerned with determining the abundance of the predominant ions, the assumption made is adequate.

The equations to be solved for hydrogen and helium are

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$$N(X^0) \int_{\nu_0}^{\infty} \pi F_\nu (r_*/r)^2 a_\nu(X^0) \exp\{-\tau_1 f_{1\nu} - \tau_2 f_{2\nu}\} d\nu = \alpha_B(X^0) N_e N(X^{+1}). \quad (8)$$

Where τ_1 and τ_2 are the optical depths of hydrogen and helium at their respective threshold frequencies, and are given by

$$d\tau_1 = N(H^0)\ a_{\nu_0}(H^0)\, dr$$

and (9)

$$d\tau_2 = N(He^0)\ a_{\nu_0}(He^0)\, dr;$$

$f_{1\nu}$ and $f_{2\nu}$ are the frequency dependences of the photoionization cross sections normalized to unity at threshold $\left[\text{we have used } f_\nu = \gamma\left(\frac{\nu_0}{\nu}\right)^s + (1-\gamma)\left(\frac{\nu_0}{\nu}\right)^{s+1}\right]$; and $\alpha_B = \sum_{n=2}^{\infty} \alpha_n$ is the recombination coefficient to all excited levels. The atomic parameters used, a_{ν_0}, γ, s and α_B, are given in Table 1.

The problem is thus expressed by two simultaneous first order differential equations

$$G_p\left(\frac{d\tau_1}{dr}, \frac{d\tau_2}{dr}, \tau_1, \tau_2, r\right) = 0 \quad ; \quad p = 1,2 \quad (10)$$

that have to be solved.

The frequency integrals were divided into two intervals $(\nu_1 - 1.808\,\nu_1)$ and $(1.808\,\nu_1 - 4\,\nu_1)$ and solved by 4-point Gauss-Legendre quadratures. A fourth-order Runge-Kutta method was employed to solve the differential equations. The derivatives $d\tau_1/dr$ and $d\tau_2/dr$ required by this method were obtained by a modified Newton-Raphson iteration procedure.

From the ionization structure of H and He the structure of the heavy elements was derived. From equation (6)

$$R(X^{+m+1}) \equiv \frac{N(X^{+m+1})}{N(X^{+m})} = \frac{\int_{\nu_0}^{\infty} 4\pi J_\nu\ a_\nu(X^{+m})\, d\nu}{N_e \alpha(X^{+m})} \quad (11)$$

where N_e and J_ν (taken to be equal to $J_\nu^{(s)}$) are obtained from equations (8).

The fractional abundance of element X in the m^{th} state of ionization is given by

$$\frac{N(X^{+m})}{N(X)} = \frac{R(X^{+1})R(X^{+2})\ldots R(X^{+m})}{[1 + R(X^{+1}) + R(X^{+1})R(X^{+2}) + \ldots]} \quad (12)$$

The atomic parameters for the heavy elements are also given in Table 1. Most of the data for the heavy elements have been obtained from MacAlpine (1972,1973). The data for argon are only crude estimates.

TABLE 1

ATOMIC PARAMETERS

Ion	$h\nu_0$* (eV)	a_{ν_0} (10^{-18} cm^2)	γ	s	α† (10^{-12} cm^{3}s^{-1})
H I	13.598	6.30	1.338	2.99	.258‡
He I	24.587	7.84	1.663	2.05	.272‡
C I	11.260	12.19	3.317	2.0	.263
C II	24.383	4.60	1.950	3.0	1.51
C III	47.887	1.60	2.6	3.0	4.18
N I	14.534	11.42	4.29	2.0	.254
N II	29.601	6.65	2.86	3.0	1.48
N III	47.448	2.06	1.63	3.0	4.04
O I	13.618	9.05	4.378	1.5	.238
O II	35.117	7.32	3.837	2.5	1.44
Ne I	21.564	5.35	3.769	1.0	.202
Ne II	40.962	7.39	2.717	1.5	1.32
Mg I	7.646	1.2	3.0	14.0	.232
Mg II	15.035	0.240	3.708	0.91	1.28
S I	10.360	5.80	2.849	1.35	.238
S II	23.33	17.8	1.384	1.86	1.32
S III	34.83	6.00	1.085	2.67	3.52
S IV	47.30	0.669	0.30	3.0	7.00
Ar I	15.755	29. :	1. :	3.:	.251
Ar II	27.62	20. :	1. :	3.:	1.33
Ar III	40.90	2. :	1. :	3.:	3.53

* Taken from Allen (1973).
† At $T_e = 10\,000$°K.
‡ α is α_B.

III. CHARGE TRANSFER

a) *General Considerations*

The ionization equilibrium equation (6) only considers photoionization and recombination processes. Recently the importance of charge transfer processes in determining the ionization of some of the heavy elements has been recognized.

Field and Steigman (1971) developed a formulation based on the orbiting approximation and calculated the rate coefficients for the charge ex-

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change process $O^0 + H^+ \rightleftarrows O^+ + H^0$. Steigman, Werner and Geldon (1971) calculated the corresponding rate for $N^0 + H^+ \rightleftarrows N^+ + H^0$.

In order to include these processes, the ionization equilibrium equation relating the neutral and once ionized species for oxygen and nitrogen can be expressed as

$$N(X^0)\left[\int_{\nu_0}^{\infty} 4\pi J_\nu a_\nu(X^0)\,d\nu + N(H^+)\beta\right] = N(X^+)\,[N_e\alpha(X^0) + N(H^0)\beta'], \qquad (13)$$

where β and β' are the respective charge transfer coefficients. In Table 2 we present the rate coefficients for N and O used in the models under consideration.

TABLE 2
CHARGE TRANSFER REACTION RATES*

	$\beta(10^{-9}\ cm^3s^{-1})$	$\beta'(10^{-9}\ cm^3s^{-1})$
O	0.91	1.04
N	0.53	0.37

* At $T_e = 10\,000$°K.

A similar process of charge transfer between carbon and helium has been proposed (Brown 1972):

$$C^{+2} + He^0 \rightarrow C^+ + He^+.$$

However Steigman (1974) has pointed out that processes of the type $X^{+2} + Y^0 \rightarrow X^+ + Y^+$ which are endothermic have an extremely low probability of occurrence at low temperatures. In the exothermic channels (the reverse reaction: $X^+ + Y^+ \rightarrow X^{+2} + Y^0$) there is a coulomb barrier which suppresses the reaction at low energies. Since the two channels are connected by detailed balance, the rate of the endothermic reaction is exponentially small.

For the case of sulphur the reaction

$$S^{++}(^3P) + He^0 \rightarrow S^+ + He^+$$

is analogous to the one studied by Brown. It is an endothermic reaction by $\Delta E = -1.26$ eV, and according to the above discussion it is not important at $T \simeq 10^4$ °K.

Another reaction of interest is

$$S^{++}(^1D) + He^0 \rightarrow S^+ + He^+;$$

it is exothermic by $\Delta E = 0.15$ eV and has a higher reaction rate than that from the ground level. The relative population of the excited level ^1D to the ground level is

$$\frac{N(^1D)}{N(^3P)} = \frac{5}{9}\,\frac{\exp-(15\,300/T)}{1 + 1.04\times10^6/N_e}$$

according to the atomic data by Garstang (1968) and Aller and Czyzak (1968). However this level is significantly populated only for high densities ($N_e \geq 10^6$ cm^{-3}) and moderately high temperatures ($T \geq 10\,000$ °K). Moreover for the case of exothermic reactions the crossing of the potential curves of the initial and final states occurs at $R_c \simeq e^2/\Delta E = 14.4(\text{Å})/\Delta E(\text{eV})$. In the case that $R_c \leq 12$ Å there may be a finite probability for the electron to be exchanged at distances $r \simeq R_c$ (Steigman 1974). For the reaction $S^{++}(^1D) + He$, $R_c \simeq 96$ Å, and there is no overlap between the initial and final wave functions.

For the densities and temperatures that interest us in this paper, the charge transfer mechanism involving carbon and sulphur is not important in comparison with the recombination rates, $\alpha(C^+)$ and $\alpha(S^+)$, given in Table 1.

IV. MODEL H II REGIONS

We have computed the ionization structure of H, He, C, N, O, Ne, Mg, S and Ar for spherical nebulae of uniform temperature and density. In all the considered cases we have taken $T_e = 10\,000$°K and $N(He)/N(H) = 0.10$. For the spectrum of the exciting star we have used the emergent fluxes given by Mihalas (1972) for non-LTE model atmospheres of effective temperatures from 30 000°K to 35 000°K and log g = 4.0.

In Table 3 we present the characteristics of the computed model H II regions. We adopted stellar radii corresponding to main sequence objects. We

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TABLE 3
CHARACTERISTICS OF THE COMPUTED H II REGIONS

T_* (10^3 °K)	r_* ($R_\odot$)	P_H (phot s^{-1})	R (pc)		
			$N(H) = 1$ cm^{-3}	$N(H) = 10^2$ cm^{-3}	$N(H) = 10^4$ cm^{-3}
30	9.4	1.77 (47)	1.78 (1)	8.25 (−1)	3.83 (−2)
32.5	10.0	1.22 (48)	3.38 (1)	1.57 (0)	7.28 (−2)
35	10.5	3.68 (48)	4.88 (1)	2.27 (0)	1.05 (−1)

also present the total flux of hydrogen ionizing photons produced by the exciting star

$$P_H = 4\pi\, r_*^2 \int_{\nu_1}^{\infty} \pi F_\nu d\nu, \qquad (14)$$

as well as the characteristic radius of the nebula

$$R = \left[\frac{3}{4\pi} P_H / N(H)^2 \alpha_B(H^0)\right]^{1/3}. \qquad (15)$$

In Figure 1 we present the detailed ionization structure of an H II region of $N(H) = 100$ cm^{-3} excited by a star of 35 000°K. In these computations the charge transfer processes for oxygen and nitrogen have been taken into account.

In general, charge transfer processes between any atom and hydrogen are important mainly at the hydrogen ionization edge, and thus do not alter significatively the total abundance of ions already present in inner regions. This effect is important for the prediction of emission lines of [N I] and [O I] since for collisional excitation to occur it is necessary that the neutral species exist within the H II region.

In the case of N (the results for O are similar) it follows that, for the range of temperatures considered, charge transfer processes hardly affect the total amount of N^+; although they increase substantially the emissivity of [N I]. However, for nebulae of higher degree of ionization (i.e. planetary nebulae) simple models predict that both N^+ and O^+ only appear close to the hydrogen ionization edge where the charge transfer mechanisms decrease considerably the once ionized species and increase the neutral ones (Williams 1973; Rodríguez 1973). From observations it is difficult to disentangle the charge transfer effects present at the hydrogen ionization edge from other processes that also are important in this region, namely, moving ionization fronts, shock waves, etc.

In Figure 2 we present the detailed structure of N^0 and N^+ with and without charge transfer in the neutral helium zone. In the same figure we include the ionization structure of helium and hydrogen.

In Figure 3 we have plotted, for the range of temperatures and densities considered, the fractional abundance of S^+ integrated over the H II region as compared to the integrated fractional abundance of the He^0,

$$\int \frac{N(S^+)}{N(S)} dV \Big/ \int \frac{N(He^0)}{N(He)} dV.$$

This quantity gives a better evaluation of the actual amount of S^+ within the neutral helium region. For a given density, variations in T_* affect this quantity by a factor of 4. Similarly, extreme variations in density (from 1 to 10^4 cm^{-3}) produce a variation of a factor of 10 in this quantity. Due to the smaller dilution factor, the degree of ionization of a nebula is lower for lower densities, and thus $N(S^+)/N(S)$ is higher.

We are usually interested in relating the observed integrated emission intensities with abundance data, and in the case of collisional excitation we can approximately assume

$$I[X^{+m}] \propto \int N_e N(X^{+m}) dV. \qquad (16)$$

Therefore, we have also plotted in Figure 3 the fractional abundance of S^+ weighted by the electron density integrated over the entire H II region,

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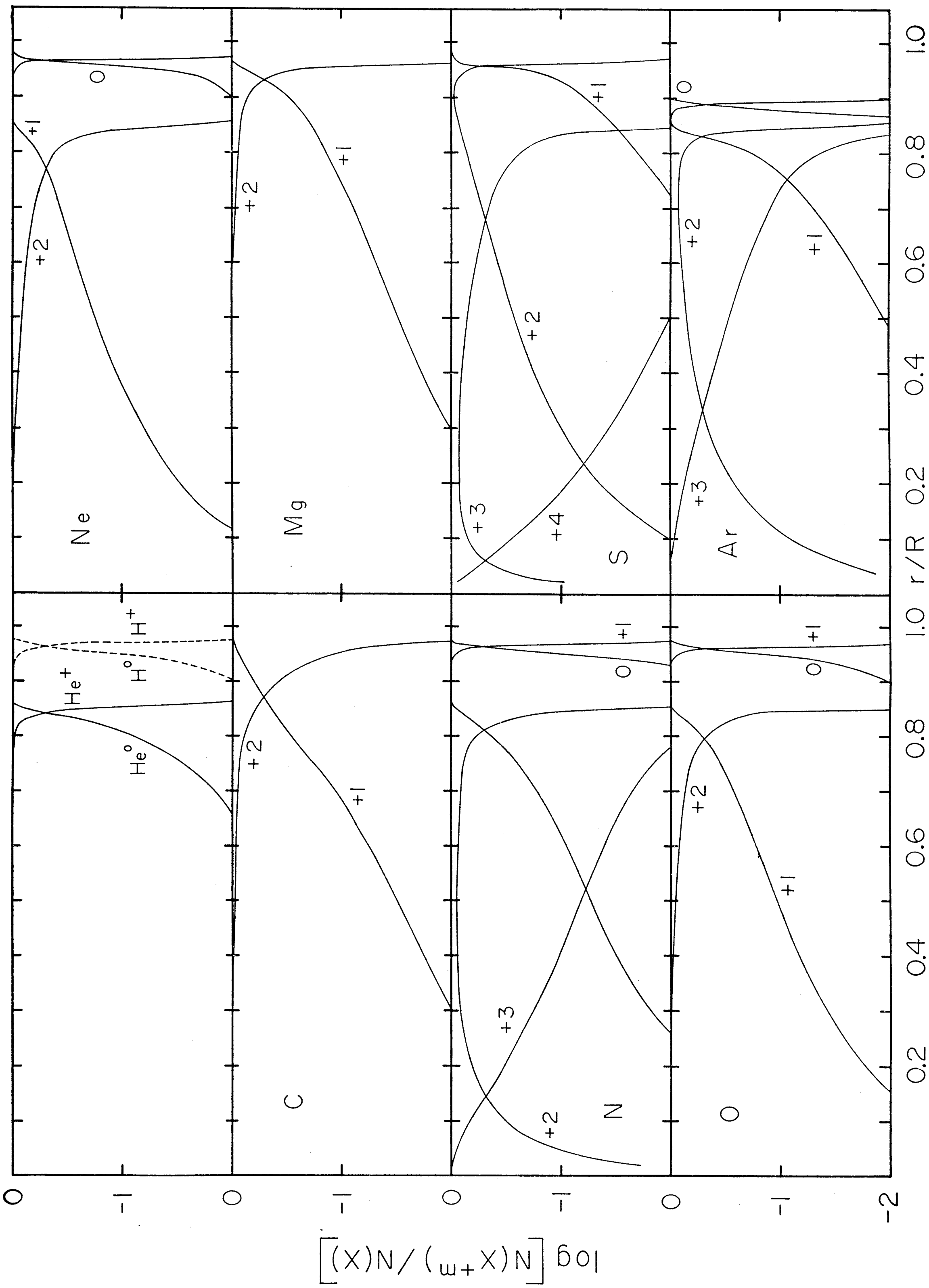

FIG. 1. Model H II region with $N(H) = 10^2$ cm^{-3} and $T_* = 35\,000$°K. Charge transfer has been considered for nitrogen and oxygen.

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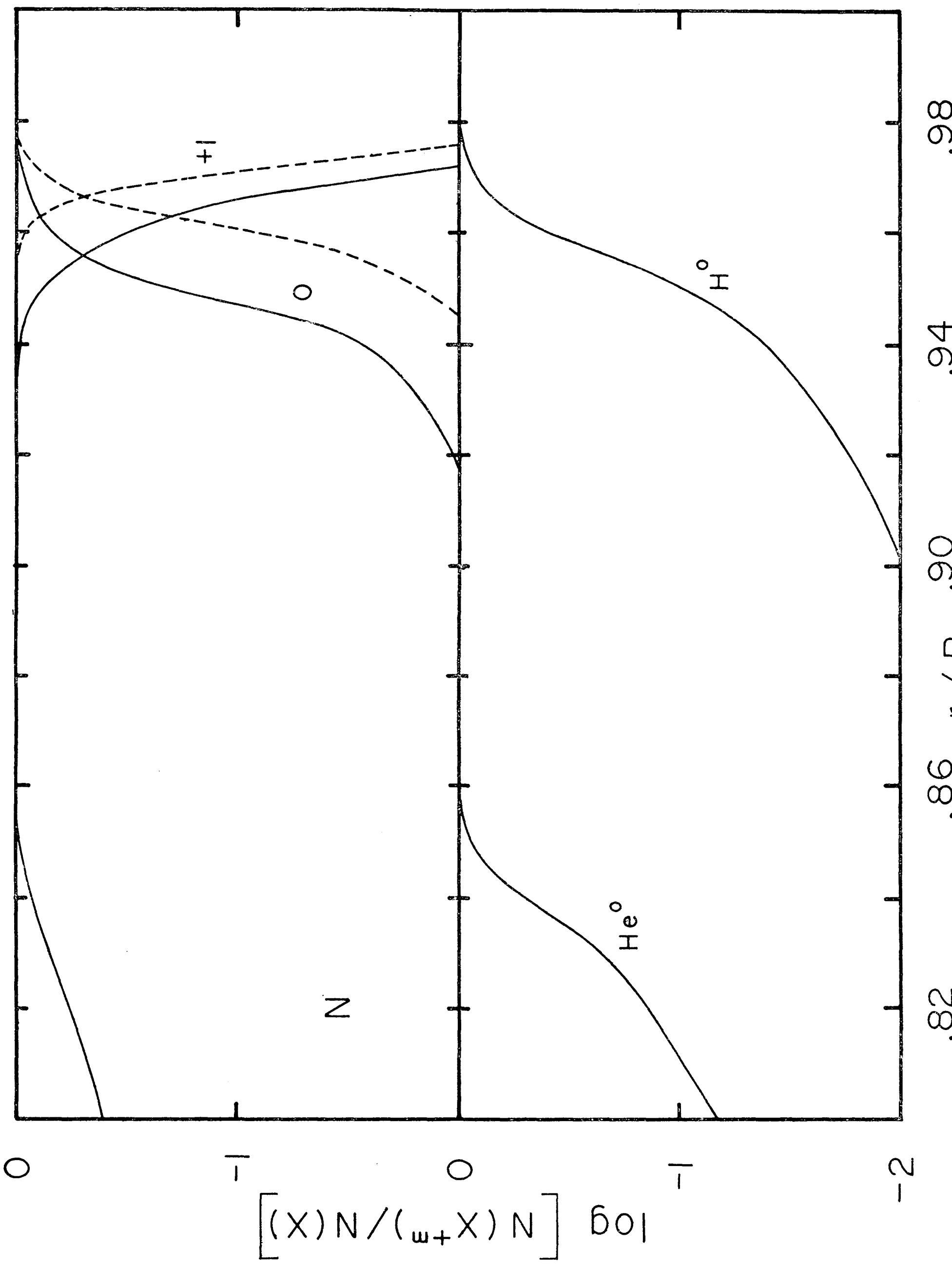

FIG. 2. Comparison of the ionization structure of nitrogen, helium and hydrogen for $N(H)=10^2$ cm^{-3} and $T_*=35\,000$°K. Solid lines correspond to computations with charge transfer; broken lines, to computations without it.

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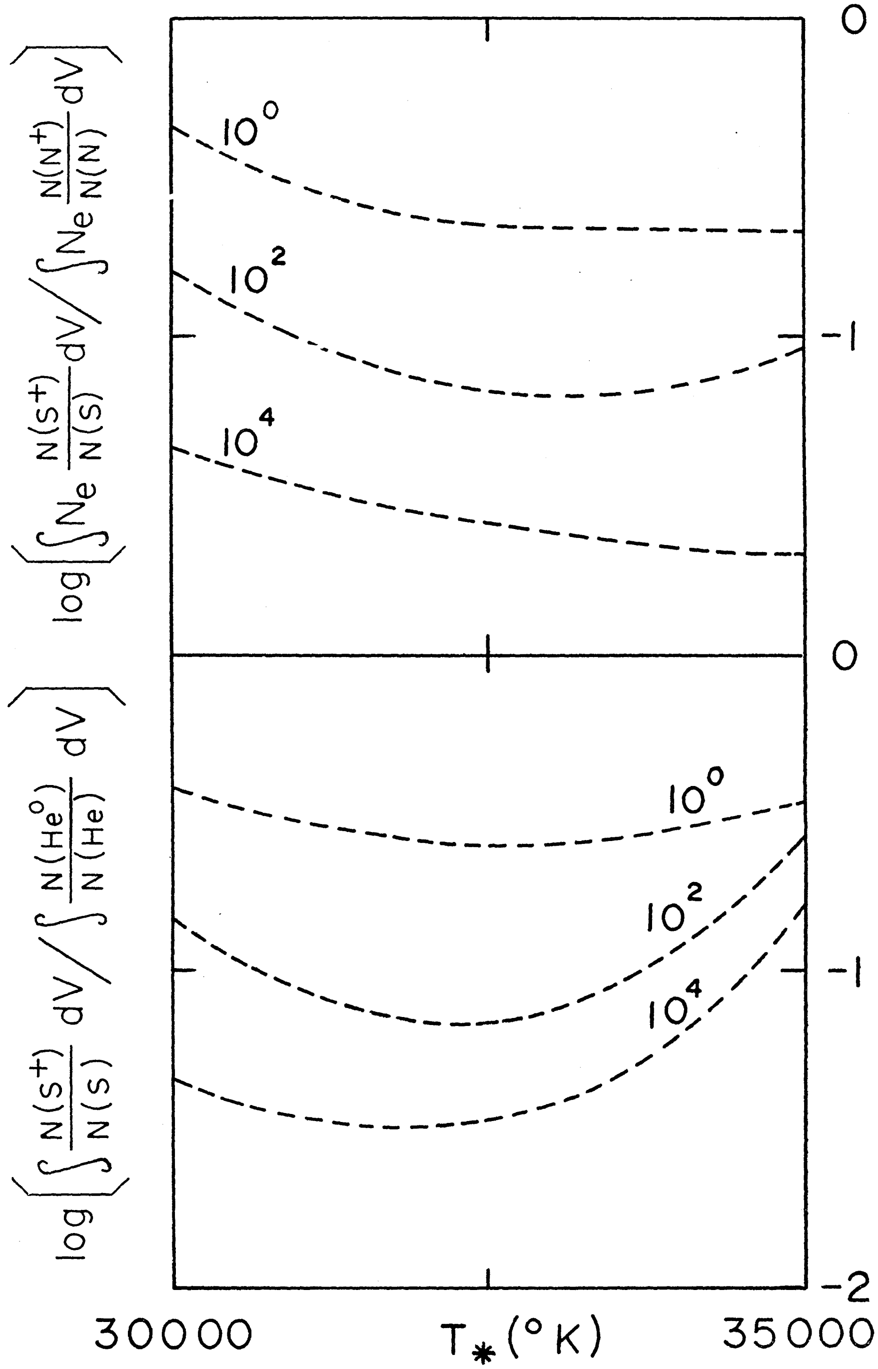

FIG. 3. Comparison of the volume fractional abundance of S^+ with those of N^+ and He^0. Numbers on the graph correspond to hydrogen densities, N(H).

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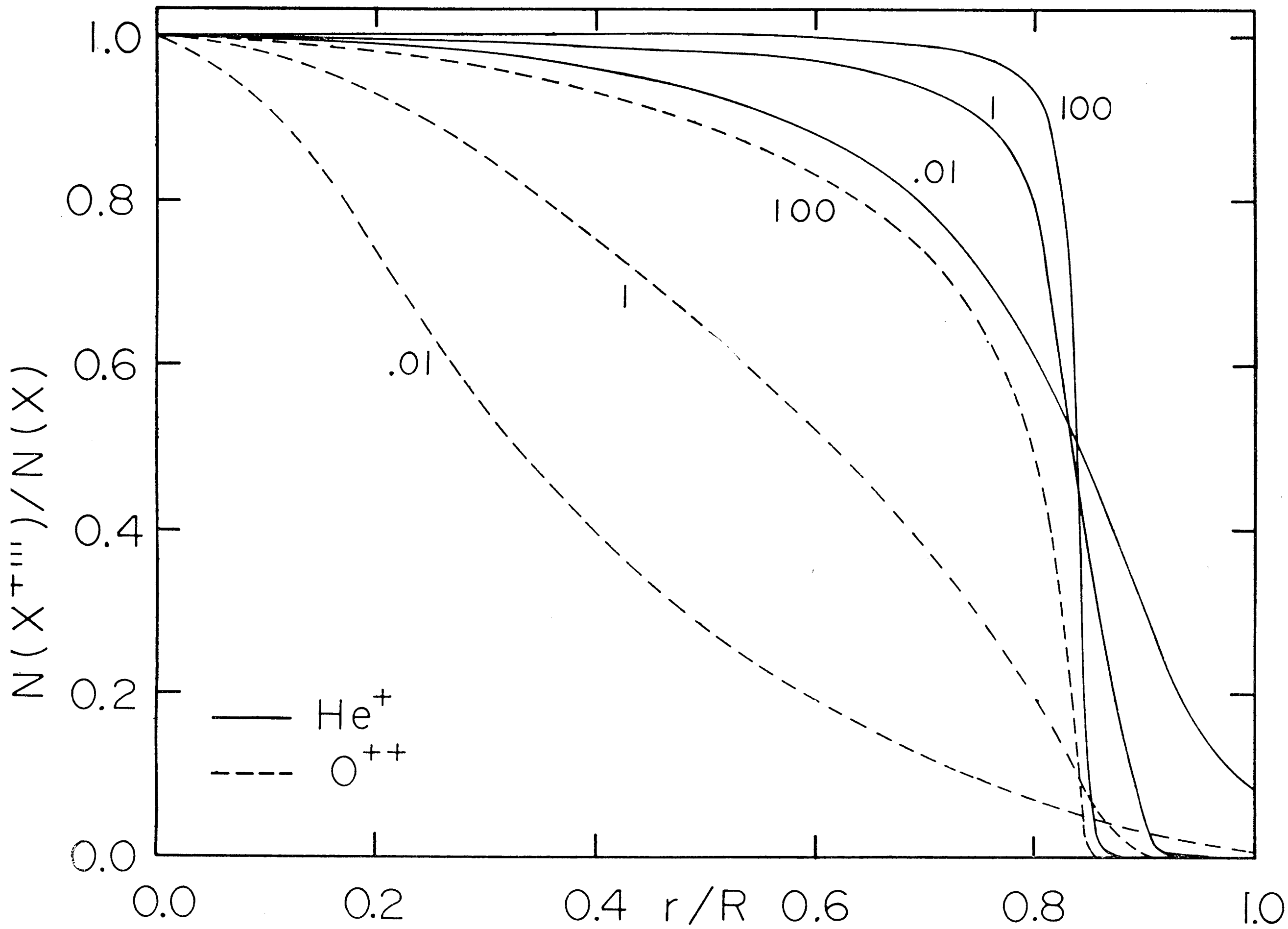

FIG. 4. Ionization structure of oxygen and helium for $T_* = 35\,000°K$. Numbers on the graph correspond to hydrogen density, N(H).

compared to the same integration for N^+, since we expect the following expression to be approximately valid

$$\int N_e \frac{N(S^+)}{N(S)} dV \Big/ \int N_e \frac{N(N^+)}{N(N)} dV \propto \frac{I[S\,II]\,N(N)}{I[N\,II]\,N(S)}. \qquad (17)$$

The total helium to hydrogen abundance ratio, $N(He)/N(H) = y$ in normal gaseous nebulae is given by

$$y = y^0 + y^+ + y^{++}, \qquad (18)$$

where

$$y^i = \frac{\int N_e N(He^i)\, dV}{\int N_e N(H^+)\, dV}. \qquad (19)$$

In the case of H II regions ionized by early O type stars, expression (18) is simplified to $y = y^0 + y^+$, where $y^+ \gg y^0$. To estimate y^0 it is necessary to derive the ionization structure of other elements observable in more than one stage of ionization, and to determine the helium ionization correction factor which is given by

$$y = i_{cf}(He)\, y^+.$$

In Figure 4 we present the ionization structure of oxygen and helium for different electron densities, and it is found that the ionization structure of the heavy elements is strongly affected by the electron density, while that of helium is not. In Figure 5 we

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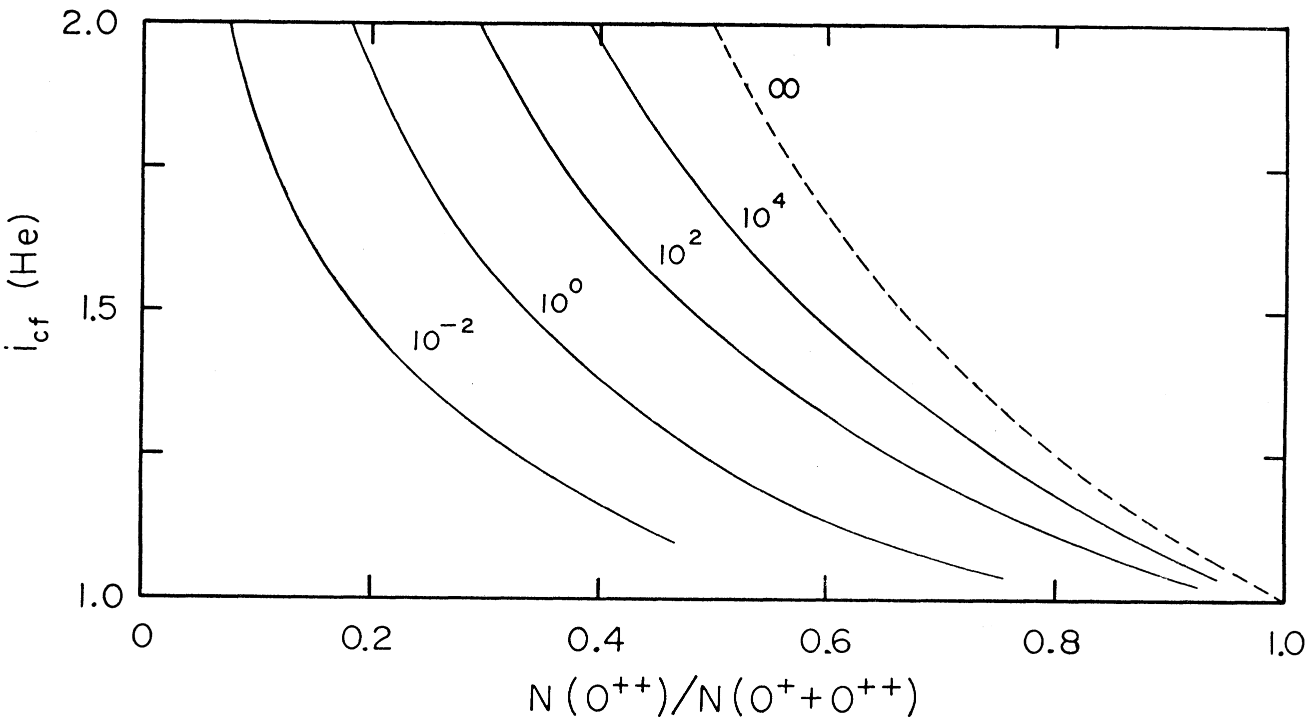

FIG. 5. Helium ionization correction factor *vs.* oxygen ionization degree. The upper part of the graph corresponds to models of low T_*, while the lower part is based on higher T_* models. Hydrogen densities are indicated on the graph.

present the dependence of the ionization correction factor of helium on the degree of ionization of oxygen, for different electron densities. From this figure, it follows that in the case of low densities, a low degree of ionization of the heavy elements does not necessarily imply a large amount of neutral helium. This result should be used to estimate the amount of neutral helium in the low density interstellar medium from the *Copernicus* satellite observations (cf. Torres-Peimbert, Lazcano-Araujo and Peimbert 1974).

V. DISCUSSION

From the observations by Peimbert and Costero (1969) it is found that S^+/N^+ is equal to 0.07, 0.11 and 0.15 for Ori I, Ori II and Ori III, respectively; the He^0/He ratio for those three points is 0.07, 0.12 and 0.31. We think that Ori III should be compared with the theoretical models because the ionization correction factors for N^+ and S^+ are smaller than for the other two points, *i.e.* N^+ and S^+ comprise a larger fraction of the observed volume. The ionizing radiation field in the direction of Ori III is mainly governed by θ^1_c and θ^2 Ori which are of spectral type O7: and O9V (Conti and Alschuler 1971) with effective temperatures around 38 000 and 34 000°K, respectively. Since in the plane of the sky θ^2 Ori is closer to Ori III than θ^1_c Ori, and the He^0/He ratio for our model of 35 000°K is 0.32, we will use our results for 35 000°K to compare the observed N^+/S^+ ratio with the theoretical one. The observations by Peimbert and Costero yield $N_e \sim 2 \times 10^3$ cm^{-3}; from this value and Figure 3, it is found that the models predict $S^+/N^+ \sim 0.03$, in poor agreement with the observations.

There are four considerations that might bridge the gap between the observational result and the theoretical prediction: 1) The observational result can be reduced if the S^+ collisional excitation cross section $\Omega(1,2)$ is larger than the one used by

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Peimbert and Costero (1969). 2) It is possible that the electron temperature in the region where the S^+ lines originate is higher than where the N^+ lines originate; Mallik (1973) has made models of ionization fronts surrounding H II regions and he has found that in these fronts the energy input time scale is smaller than the cooling time scale. Therefore, immediately after ionization, the gas is heated to a temperature considerably higher than the equilibrium temperature. This effect will increase preferentially the [S II] with respect to the [N II] line intensities, and its consideration would reduce the observed value derived by Peimbert and Costero. 3) A large cross section for the $S^{++} + He^0 \rightarrow S^+ + He^+$ charge exchange reactions would increase the theoretical prediction on the S^+/N^+ ratio; however as discussed in §III it is very unlikely. 4) Finally, from Figures 3 and 4 it can be seen that the S^+/S ratio is very sensitive to the dilution of the radiation field, while the N^+/N as well as the He^0/H ratios are not; this implies that at higher dilution factor values the S^+/N^+ ratio increases. It is possible to have larger dilution factors by lowering the electron density or by having the ionizing stars away from the nebular center, or by increasing the density fluctuations. From the work of Osterbrock and Flather (1959) it is known that there are large density fluctuations present in the Orion Nebula; these fluctuations would increase the theoretical S^+/N^+ ratio. The model of Osterbrock and Flather is based on the extreme view that only a fraction of the volume is filled with gas and the rest is empty ($f = 1/30$). There is a more recent density model by Simpson (1973) in which the nebula is divided into elements of high and low density; from this model it is found that in the inner regions that produce most of the emission at Ori III, $N_e(\text{high}) \sim 10^4$ cm^{-3} and $N_e(\text{low}) \sim 10^3$ cm^{-3} reducing considerably the effect of density fluctuations on the ionization structure.

Of the four possible explanations given, the last one seems to be the most promising, implying that the ionizing stars are located off-center with respect to the Nebula, or that the ionization structure is considerably affected by density fluctuations.

From the models in the 30 000°K to 35 000°K range presented in §IV it is found that

$$\int N_e \frac{N(O^0)}{N(O)} \, dV \Big/ \int N_e \frac{N(S^+)}{N(S)} \, dV$$

varies from approximately 1/4 to 1/16 in the case where the charge exchange reaction for oxygen is not considered; while for those cases when it is considered it varies from aproximately 1/2 to 1/6. From observations of the [O I] and [S II] lines in different objects Peimbert (1971) found a value of about 1/4 for this ratio, assuming that both lines originated at similar electron temperatures.

There are three observational results relevant to the study of [S II] lines in gaseous nebulae that should be explained by theoretical models: *a*) The large [S II]/Hα ratio. This ratio increases significantly towards the nuclei of galaxies (Peimbert 1971; Warner 1973; Rubin and Ford 1972); in particular, at a given distance from the center of M33 the fainter the H II region the higher the [S II]/Hα ratio (Benvenuti *et al.* 1973; Comte and Monnet 1974). Moreover, from ionization estimates based on the large [S II]/Hα ratios and the upper limit found by Comte and Monnet for the [O III]/Hβ ratio, it follows that S^+ comprises at least 25% of the total sulphur inside the interarm H II region in M33. *b*) The [N II]/[S II] ratio is approximately constant for H II regions at similar distances from the nucleus of M33 although both the emission measure of these objects, $\int N_e N(H^+) dl$, and N_e vary by at least an order of magnitude. The evidence on the latter variations is that the thickness of the interarm H II region, which is the faintest region detected, is at least an order of magnitude larger than the diameters of the brightest H II regions. Furthermore, the radiation fields are different since the ionization degree is lower for the fainter regions (Benvenuti *et al.;* Comte and Monnet). *c*) The [N II]/[S II] ratio increases by about two orders of magnitude from the outermost H II regions to the nuclei of spiral galaxies (Benvenuti *et al.*; Comte 1974).

The presence of large quantities of He^0 in H II regions is relatively simple to explain because for stellar temperatures lower than 36 000°K and $N(He)/N(H) = 0.10$ the He^+ sphere is smaller than the H^+ sphere. Moreover, the presence of dust particles absorbing photons able to ionize helium more efficiently than those able to ionize hydrogen

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can also help in producing a He^+ sphere smaller than the H^+ one. It is very difficult to explain the presence of substantial amounts of S^+ in radiatively ionized H II regions (like those of M33). In the first place the ionization potential of S^+ is 23.33 eV while that of He^0 is 24.59 eV. Moreover, in the regions where helium is ionized most of the sulphur is at least twice ionized while in the regions where helium is neutral there are enough ionizing photons in the 23.3 to 24.6 eV range to doubly ionize sulphur. In addition owing to the low abundance of sulphur, $N(S)/N(H) \sim 10^{-4}$, S^{++} cannot produce its own Stromgren sphere. There are two types of particles that can compete with sulphur for the photons in the 23.3 to 24.6 eV energy range: hydrogen atoms and dust particles; the cross section for photoionization of hydrogen atoms is proportional to ν^{-3}, therefore neutral hydrogen absorbs these photons mainly at the edge of the H II region, and consequently most of the sulphur would be twice ionized. For dust to increase significantly the S^+ abundances, it would be necessary that $\tau \gg 2$ for photons in the 23.3 − 24.6 eV range, and at the same time that $\tau \leq 1$ for photons more energetic than 24.6 eV, and that $\tau < 1$ for photons in the 13.6 − 23.3 eV range. These conditions are difficult to fulfil. Therefore, the large [S II]/Hα ratios observed imply the presence of extreme density fluctuations and/or low density regions.

The constancy of the [N II]/[S II] ratio in M33 apparently implies the presence of large dilution factors caused by low densities and extreme density fluctuations.

Finally, from Figure 3 it follows that in the case of radiative ionization by a single star, a change in the I[N II]/I[S II] ratio by two orders of magnitude implies a change of eight orders of magnitude on the electron density, or a change of two orders of magnitude in the N/S abundance ratio. It can be argued that the [N II]/[S II] line intensity ratios, larger in nuclei of galaxies than those of normal H II regions, could be due to the densities of the former being higher than those of the latter; however, we think it is unlikely because the density fluctuations and the [S II]/Hα ratios are larger in nuclei of galaxies than in normal H II regions (Peimbert 1968). Therefore, we conclude that the change in the I[N II]/I[S II] ratio is due to an abundance effect as suggested by Benvenuti *et al.* (1973). This result is in agreement with that of Searle (1971) who finds a N/O abundance gradient across the disks of spiral galaxies.

Since it is not clear which is the source of ionization in nuclei of galaxies, we will study the other extreme possibility: that radiative ionization is negligible, that the ionization is controlled by collisional ionization and that the recombination is due to collisional and radiative processes. Under these conditions, in the regions where sulphur is once ionized, most of the helium is neutral, and in the regions where sulphur is twice ionized, most of the helium is once ionized (House 1964). However, in the region where S^+ is once ionized, O is about 75% ionized and 25% neutral, (Peimbert 1971) and since the ionization potential of nitrogen is 14.534 eV while that of oxygen is 13.618 eV, most of the nitrogen would be once ionized also (House 1964). Since in this case the [N II] and [S II] lines originate in the same volume elements, under the same conditions of temperature, it follows that the I[N II]/I[S II] ratio is proportional to the total N/S abundance ratio.

VI. CONCLUSIONS

It is found that while the helium ionization structure is not significatively affected by changing the electron density of the models, the ionization structure of the heavy elements is considerably affected by it. Therefore to estimate the amount of neutral helium inside a given H II region we need, in addition to knowledge of the ionization structure of the heavy elements, information about the density distribution (see Figures 4 and 5).

The [O I]/[S II] line intensities predicted by our models (for electron densities in the range of 1 to 10^4 cm^{-3} and stellar temperatures in the range of 30 000 to 35 000°K) taking into account the $O^+ + H^0 \rightleftharpoons H^+ + O^0$ charge exchange reaction, are in very good agreement with the observations.

For low density H II regions it is found that the [S II] and [N II] lines originate in the same volume elements; therefore, the I[S II]/I[N II] ratios provide a powerful tool to study the N/S abundance gradient present across the disks of spiral galaxies. Moreover, if the ionization in the nuclei of galaxies

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were collisional, it would also be found that the [S II] and [N II] lines originated in the same volume elements.

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