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THE IONIZATION STRUCTURE OF H II REGIONS OF DIFFERENT HELIUM CONTENT

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RESUMEN

Se ha obtenido la estructura de ionización nebular correspondiente a $y = N(He)/N(H)$ en el intervalo de 0.07 a 0.30 y a temperaturas estelares comprendidas entre 30 000 y 45 000 °K. En todos los casos se consideró que tanto la región H II como la estrella ionizante tenían la misma y.

Se adoptó un valor pregaláctico de $y = 0.07$, $Z = 0$ y una relación evolutiva dada por $\Delta Y = 3\Delta Z$.

Un aumento en el valor fotosférico de y, para una temperatura efectiva dada, disminuye el cociente de fotones capaces de ionizar helio a fotones capaces de ionizar hidrógeno, P(He)/P(H). Consecuentemente, se encuentra que para ciertos valores de la temperature estelar el cociente nebular $N(He^+)/N(H^+)$ disminuye al aumentar y.

A partir de consideraciones de estructura estelar, se encuentra que un aumento en y, para una estrella de masa dada, produce un aumento importante en la luminosidad y temperaturas estelares; de modo que para una y mayor, y suponiendo que la función inicial de masa es única, se esperaría que en promedio las regiones H II tuvieran un grado mayor de ionización del helio.

Estos efectos son muy importantes en el estudio de los gradientes en las líneas de emisión en otras galaxias y en particular en la interpretación de la deficiencia de helio ionizado en el núcleo de nuestra galaxia. Se reseñan varias posibles explicaciones de la deficiencia de helio ionizado en el centro galáctico.

ABSTRACT

We have computed the ionization structure corresponding to H II regions and ionizing stars with $y = N(He)/N(H)$ in the 0.07 to 0.30 range and T_* in the 30 000 to 45 000 °K range.

We have adopted a pregalactic value of $y = 0.07$, $Z = 0$ and an evolutionary dependence of $\Delta Y = 3\Delta Z$.

An increase in the photospheric y value for a given effective temperature produces a decrease in the ratio of helium-to-hydrogen ionizing photons, P(He)/P(H). Consequently, it is found that for a moderate range of stellar temperatures the $N(He^+)/N(H^+)$ ratio in the nebula decreases as y increases.

From stellar structure considerations it is found that an increase in y, for a star of a given mass, produces a significant increase in the stellar luminosity and effective temperatures; therefore for a higher value of y, and for a constant mass function, on the average the H II regions would have a higher degree of ionization of helium.

These effects are very important in the study of emission line gradients in external galaxies; and in particular, in the study of the lack of ionized helium in the nucleus of our galaxy. Several explanations for the lack of ionized helium in the center of our galaxy are reviewed.

Key words: ABUNDANCES — EARLY-TYPE STARS — GALACTIC NUCLEI — NEBULAE.

I. INTRODUCTION

Peimbert and Torres-Peimbert (1974) found that in the galactic neighborhood the pregalactic helium to hydrogen ratio, y_p, is equal to about 0.07 and that $y = 0.101$ for the Orion Nebula. From these results, as well as from the corresponding Z values, they concluded that the chemical evolution of galaxies is characterized by $\Delta Y/\Delta Z \simeq 3.3$.

Searle (1971) has found that there is a N/O abundance gradient across the disk of spiral galaxies extending from the outermost to the innermost normal H II regions. Furthermore Benvenuti, D'Odorico and Peimbert (1973) found a N/S abundance gradient extending through the entire disk of spiral galaxies; this gradient being more pronounced near the nuclei. Independent evidence in favor of the existence of abundance gradients near, and within, the nuclei of galaxies, has also been presented on the basis of stellar absorption features (Mc Clure 1969; Spinrad *et al.* 1971; Spinrad *et al.* 1972). From these results it is expected that in the nuclei of some spiral galaxies such as M51, M81 and possibly ours, $Z_{nucleus}/Z_{Orion} \sim 3$ to 6.

The $^{12}C/^{13}C$ ratio has been derived in the direction of the galactic center. In Sgr B2 the +62 km s^{-1} cloud yields a carbon isotopic ratio of 14 ± 5, and in Sgr A the +42 km s^{-1} cloud a ratio of 18 ± 10 (Bertojo, Chui and Townes 1974). These values are substantially lower than the terrestrial and solar neighborhood ratios. This result implies that the chemical evolution in the center of the galaxy has been considerably more efficient than in the solar neighborhood (Torres-Peimbert and Peimbert 1971; Wollman 1973) and supports the hypothesis that the Z value in the nucleus of our galaxy is considerably higher than that in the solar neighborhood.

From these arguments, and assuming that the $\Delta Y/\Delta Z$ found by Peimbert and Torres-Peimbert (1974) applies also in the cases of large Z, it is expected that in the nucleus of M51, M81 and probably of our own galaxy, $y \sim 0.2$ to 0.3.

On the basis of these considerations we decided to study the ionization structure of normal H II regions with different y values, adopting the same y for the H II region and the ionizing star. In what follows we will adopt $y_p = 0.07$ and $\Delta Y/\Delta Z = 3$ for the models under consideration.

II. MODEL H II REGIONS

a) *General Considerations*

We have computed the ionization structure of H and He, as well as that of the heavy elements C, N, O, Ne, Mg, S and Ar, for the case of a spherical nebula of uniform temperature and density. We have considered different values of T_* of the exciting star in the range of 30 000 to 45 000 °K. In all cases we have taken $N(H) = 100$ cm^{-3} and we have adopted stellar radii corresponding to main sequence stars. A grid of models was obtained for different chemical compositions of the system. In each case considered, the emergent flux used for the exciting star was that corresponding to the composition adopted for the nebula. Variations in y for the same effective stellar temperature strongly affect the ionization structure of the nebula owing both to the different emergent fluxes at $h\nu \geq 24.58$ eV and to the different rate of helium recombination within the nebula.

The computations were carried out using the treatment described by Peimbert, Rodríguez and

TABLE 1

ADOPTED PARAMETERS*

y	Y	Z	Assumed T_e(°K)
0.07	0.22	0.00	18 000
0.10	0.28	0.02	8 500
0.15	0.34	0.04	7 000
0.30	0.49	0.09	6 000

* Assuming $y_p = 0.07$ and $\Delta Y = 3\Delta Z$.

Torres-Peimbert (1974), hereinafter referred to as Paper I. Several aspects of this treatment were reconsidered (details will be given below): i) Given the higher helium content of some of the models, a more rigorous treatment was given to the diffuse radiation. ii) As the cooling rate of the nebula depends on its heavy element content we assigned to each case the electronic temperatures given in Table 1. iii) The validity of the usual hypothesis that the heavy elements do not affect directly the radiation field was discussed.

We have dealt with the diffuse radiation by assuming that H I Ly-continuum, He I Ly-α and

Ie I two-quantum emission are reabsorbed " on the pot" by H I, while He I Ly-continuum, although eabsorbed "on the spot", was taken as being shared y the two possible absorbers; H I and He I. We ave taken the source function to be

$$J_\nu^{(d)} = \frac{\sum_i j_\nu(i)}{\kappa_\nu}, \qquad (1)$$

where the summation is carried out over the four nechanisms considered and the opacity is given by

$$\kappa_\nu = N(H^0)\,a_\nu(H^0) + N(He^0)\,a_\nu(He^0). \qquad (2)$$

The main effect of using these relations is to increase he size of the H^+ sphere in comparison with models where the diffuse photons due to He I Ly-α and He I two-quantum emission are neglected. In the ases of high helium abundance this increase is ubstantial.

The consideration of the diffuse radiation in the hotoionization of the heavy elements alters mainly he proportion between the lower ionization stages, ince diffuse radiation tends to be concentrated in he lower frequencies just above the Lyman limit cf. Aller, Menzel and Pekeris 1939); while the bundance of the higher stages is dominated by the tellar radiation. The global results are barely nfluenced by this effects since the highest possible onization stages are usually the predominant ones.

In order to take into account the dependence of the recombination rates on the electronic temperature, we have modified the recombination coefficients given in Paper I, by the factor $(T_e/10\,000)^{-0.84}$.

The assumption that the heavy elements do not lirectly affect the radiation field (and can be treated is a perturbation) can be critically tested for the $C^+ - C^{+2}$ ionization structure in nebulae where here exists an outer He^0 region in which no radiation of $\nu \geq 1.808\nu_1$ is present. In this case, C^+ can only be ionized by the small fraction of photons that lie between $1.793\nu_1$ (its ionization threshold) and $1.808\nu_1$. Other important ions that have available a imited frequency range for photoionization are S^+ and Cl^+ (ionization thresholds at $1.721\nu_1$ and $1.751\nu_1$, espectively); nevertheless we will confine our discussion to C. We propose that the perturbation hypothesis is valid as long as

$$\frac{P_{C^+\text{-He}}}{P_{H\text{-He}}} \equiv \frac{4\pi r_*^2 \int_{1.793\nu_1}^{1.808\nu_1} \pi F_\nu d\nu}{4\pi r_*^2 \int_{\nu_1}^{1.808\nu_1} \pi F_\nu d\nu} \geq \frac{\int N_e N(C^{+2})\,\alpha(C^+)\,dV}{\int N_e N(H^+)\,\alpha_B(H^0)\,dV}, \qquad (3)$$

where r_* is the stellar radius and πF_ν is the emergent stellar flux in photons s^{-1} cm^{-2} hz^{-1}. In expression (3) the volume integrations are carried out over the region where helium is neutral and hydrogen ionized. The proposition seems reasonable because H^0 absorbs preferentially photons of the lowest available frequency, interfering with the radiation in the range $1.793\nu_1$ to $1.808\nu_1$ only at the very outer regions. Under the assumption that C and H are predominantly in the forms of C^{+2} and H^+ in the volume considered, and that regardless of T_e

$$\alpha(C^+) \sim 6\,\alpha_B(H^0),$$

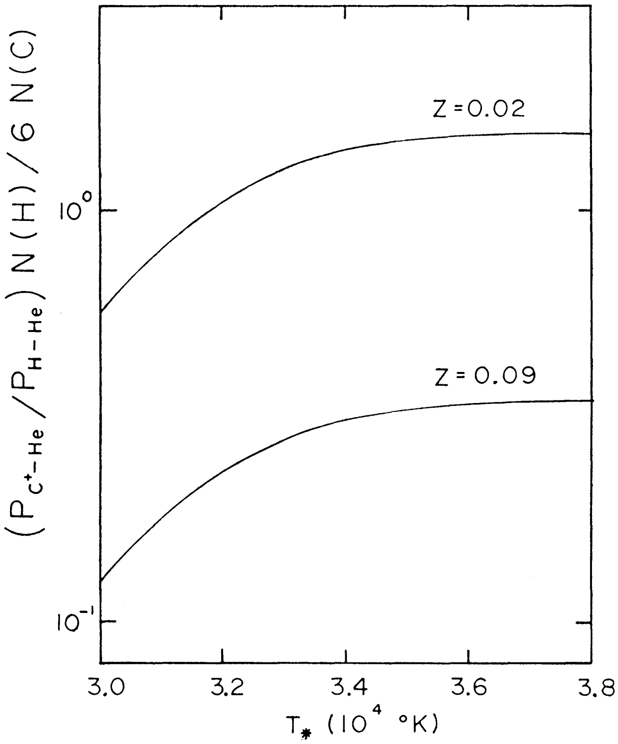

FIG. 1. The criterion for validity of the perturbation hypothesis, given by expression (4), as a function of stellar temperature.

then condition (3) would take the simpler form

$$\frac{1}{6}\frac{N(H)}{N(C)}\frac{P_{C^+-He}}{P_{H-He}} \geq 1, \qquad (4)$$

for the perturbation hypothesis to hold. In the extreme case of $Z = 0.09$, $y = 0.30$ and assuming that the proportions between the heavy elements are the cosmic ones, we have that $N(C)/N(H) \simeq 0.004$.

In Figure 1 we present, for the range 30 000 to 38 000 °K and for $Z = 0.02$, 0.09 for the nebula, the ratio defined in expression (4) using the stellar model atmospheres by Mihalas (1965). These model atmospheres were obtained for LTE, $\log g = 4.0$, and $Z = 0$. From this figure it is clear that at high Z values the approximation breaks down and carbon can become optically thick and form its own Stromgren sphere. Moreover, the presence of the heavy elements in the stellar atmosphere creates discontinuities of the stellar flux, increasing the possibility of this effect. Nevertheless, in this paper, we treat carbon only as a perturbation. In the case of S and Cl we found that, even in the high Z model, the perturbation approximation remains valid.

b) *Computations for different y*

We studied the effects of variations in the helium abundance on the ionization structure of H II regions using the model atmospheres by Mihalas (1965). These stellar fluxes were computed for a $y = 0.05$, 0.15 and 0.30 under the assumption of LTE and no heavy elements, $Z = 0$. For the range of stellar temperature from 30 000 to 40 000 °K, an increase in the helium abundance, for a given T_*, decreases the emergent flux of helium ionizing photons. This occurs because the opacity is increased at frequencies greater than $1.808\nu_1$. At higher temperatures, helium in the stellar atmosphere is highly ionized, and this effect disappears. The effect on the emergent flux between ν_1 and $1.808\nu_1$ is negligible. In Figure 2 we present the dependence on stellar temperature of the ratio of helium to hydrogen ionizing photons

$$\frac{P(He)}{P(H)} \equiv \frac{4\pi r_*^2 \int_{1.808\nu_1}^{\infty} \pi F_\nu d\nu}{4\pi r_*^2 \int_{\nu_1}^{\infty} \pi F_\nu d\nu}, \qquad (5)$$

for different y values and for $\log g = 4.0$.

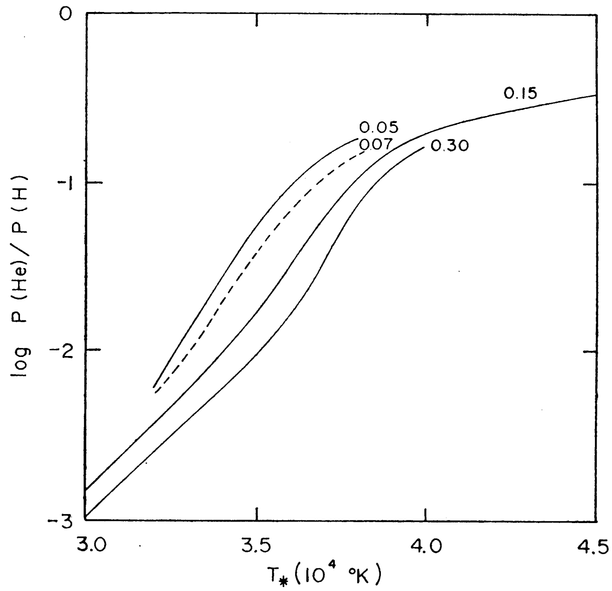

FIG. 2. Ratio of helium to hydrogen ionizing photons as a function of stellar temperature. Numbers on the figure correspond to N(He)/N(H) in the stellar atmosphere. Data taken from Mihalas (1965).

In Figure 3 we present the ionization structure of H and He or $T_* = 38\,000$ °K, $\log g = 4.0$ and $y = 0.07$ and 0.30. The spectrum for $y = 0.07$ is interpolated from the models by Mihalas (1965). In the case of low y the H^+ and He^+ spheres are practically coincident, while in the case of high y most of the hydrogen ionized volume is occupied by He^0. In this and other figures, we have used the characteristic radius of the nebula as defined by

$$R = [3\,P(H)/4\pi\,N(H)^2\,\alpha_B(H^0)]^{1/3}.$$

For convenience, we define the fractional abundance of helium ions within the H II region as

$$y^{+1} \equiv \frac{\int N_e N(He^{+1})\,dV}{\int N_e N(H)\,dV} \qquad (6)$$

such that

$$y = y^0 + y^{+1} + y^{+2}. \qquad (7)$$

In equation (6) the volume integrations are carried out throughout the ionized volume. For a normal H II region N(H) is approximately equal to $N(H^+)$.

We are usually concerned with comparing models with observed line intensities. Thus for a nebula the

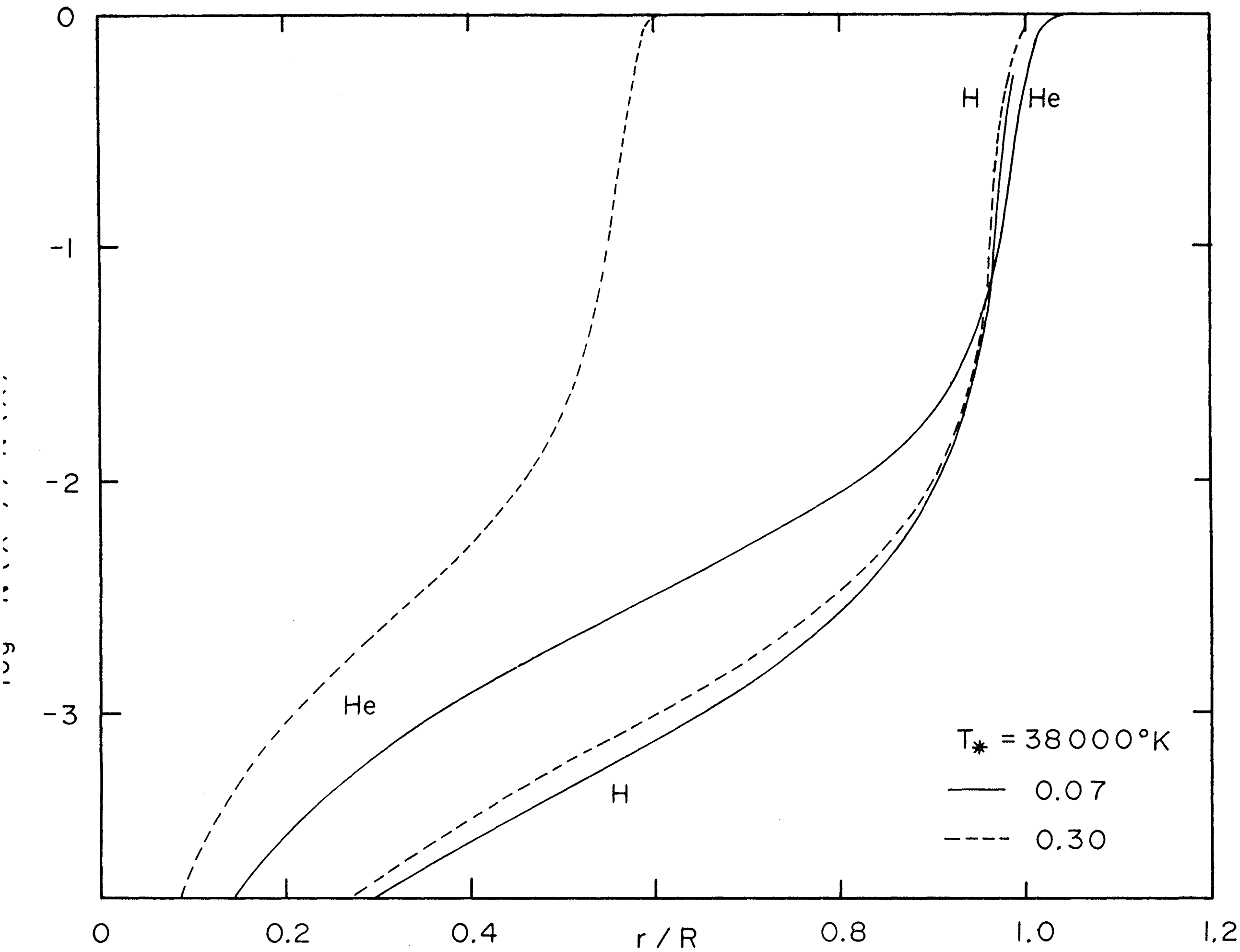

FIG. 3. Detailed ionization structure of H and He. $T_* = 38\,000$ °K, N(He)/N(H) = 0.07 and 0.30.

following integrated ratio is expected to be directly comparable to observations

$$\frac{I\,(\mathrm{He\,I})}{I\,(\mathrm{H\,I})} \propto \frac{\int N_e N(\mathrm{He}^+)\,dV}{\int N_e N(\mathrm{H}^+)\,dV} = y^+ . \qquad (8)$$

We present in Figure 4 the y^+ obtained from models of ionization structure for different values of y as a function of stellar temperature. For $T_* \leq 37\,000$ °K, a lower ratio of helium to hydrogen integrated line emission corresponds to a larger helium abundance of the system. For $T_* \geq 40\,000$ °K this condition is reversed. The emissivities of the recombination lines of H^0 and He^0 depend similarly on T_e and therefore any change in T_e does not affect this result. The minimum T_* for coincidence of the spheres of H^+ and He^+ depends on the value of y. For $y = 0.07$, this temperature is approximately 36 000 °K, for $y = 0.15$ it is 39 000 °K, and for $y = 0.30$ it is 44 000 °.

It is well known that there is the selection effect that observations are usually made of regions excited by the hotter, intrinsically more luminous, stars since these regions would have substantially larger radii and emission measures. In this case the degree of helium ionization would be high and the observed regions would correspond to the right hand side of Figure 4; this is particularly the case for giant metal-poor H II

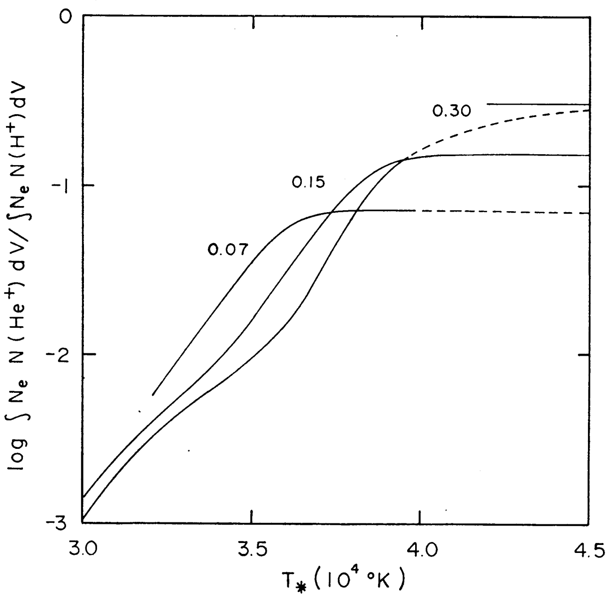

FIG. 4. Ratio of He^+ to H^+ integrated nebular abundances, y^+. Numbers on the figure correspond to N(He)/N(H) for both the stellar atmosphere and the nebula.

regions. However, in giant metal-rich H II regions the helium ionization degree is lower (Peimbert 1975) and the left hand side of Figure 4 becomes relevant. The presence of neutral helium in metal-rich H II regions might be due to lower stellar temperatures of the ionizing stars and/or to the presence of dust particles that absorb preferentially those photons capable of ionizing helium than those capable of ionizing hydrogen.

It should be mentioned that many O stars are not in hydrostatic equilibirium as evidenced by the phenomenon of stellar winds indicated by P Cygni profiles. It is possible that the emergent fluxes predicted under the assumption of hydrostatic model atmospheres might be substantially altered when this hypothesis is removed; in particular, there could be many emission lines present at $\nu > \nu_1$.

i) *Effects of different Z*

In general we are interested in studying the effect of variations in helium abundance coupled to variations in the heavy element abundances. We need thus to study the effect of an increase in Z on the photon flux emerging from the star.

We have interpolated to $y = 0.10$ and $T_* =$ 32 500, 35 000 and 37 500 °K the stellar fluxes calculated assuming LTE and $Z = 0$ (Mihalas 1965) and compared them to the corresponding fluxes for LTE and $Z = 0.013$ (Mihalas 1972). The variation from $Z = 0$ to $Z = 0.013$ does not significantly change the ratio P(He)/P(H). We do not have available a grid of model atmospheres for $Z > 0.013$ compatible with the models used here. However, from the work by Hummer and Mihalas (1970) it is found that for 40 000 °K and log g = 4.5 an increase in Z from 0.0055 to 0.019 causes a variation in P(He) and P(H) only by factors of 0.92 and 0.99, respectively.

Alternatively, the presence of heavy elements in the atmosphere significantly changes the emergent flux at selected frequency ranges. For instance, in the models by Mihalas (1972) the effect of the presence of heavy elements in the stellar atmosphere has been included by proposing a single "average" element that has atomic properties obtained from averaging those of C, N and O. This "average" element has ionization potentials at ν_1, $2.26\nu_1$, $3.53\nu_1$ and $5.68\nu_1$. The first ionization potential coincides with that of H and we cannot disentangle the individual effects. Also for the range of stellar temperatures under consideration, the radiation of $\nu > 4\nu_1$ is negligible, and only the discontinuities at $2.26\nu_1$ and $3.53\nu_1$ can be studied. The importance of the discontinuity can be measured by the quantity $D_\nu = \log F_{\nu-}/F_{\nu+}$. For the case of log g = 4.0 and T_* of 32 500, 35 000 and 37 500 °K the value of $D_{2.26\nu_1}$ is 0.099, 0.136 and 0.044, while that of $D_{3.53\nu_1}$ is 0.46, 2.63 and 2.86, respectively. That is, the discontinuity at $2.26\nu_1$ is small and it does not affect the ionization structure of the heavy elements; but even for this moderate value of Z, the large discontinuity at $3.53\nu_1$ substantially affects the ionization structure of elements that have ionization potentials close to $3.53\nu_1$ (mainly C, at $3.52\nu_1$ and N, at $3.49\nu_1$). In Figure 5 we present the fractional abundance of C^{+2} and N^{+2} for $T_* = 37\,500$ °K, both for $Z = 0$ and $Z = 0.013$, in the stellar atmosphere. In the case of $Z = 0$, C^{+3} and N^{+3} are the predominant stages within the nebula. In the case of $Z = 0.013$, most of the carbon and nitrogen in the nebula are in the form of C^{+2} and N^{+2}, since practically no radiation of $\nu > 3.53\nu_1$ exists. These details will have to be considered in order to interpret the observations of the ultraviolet

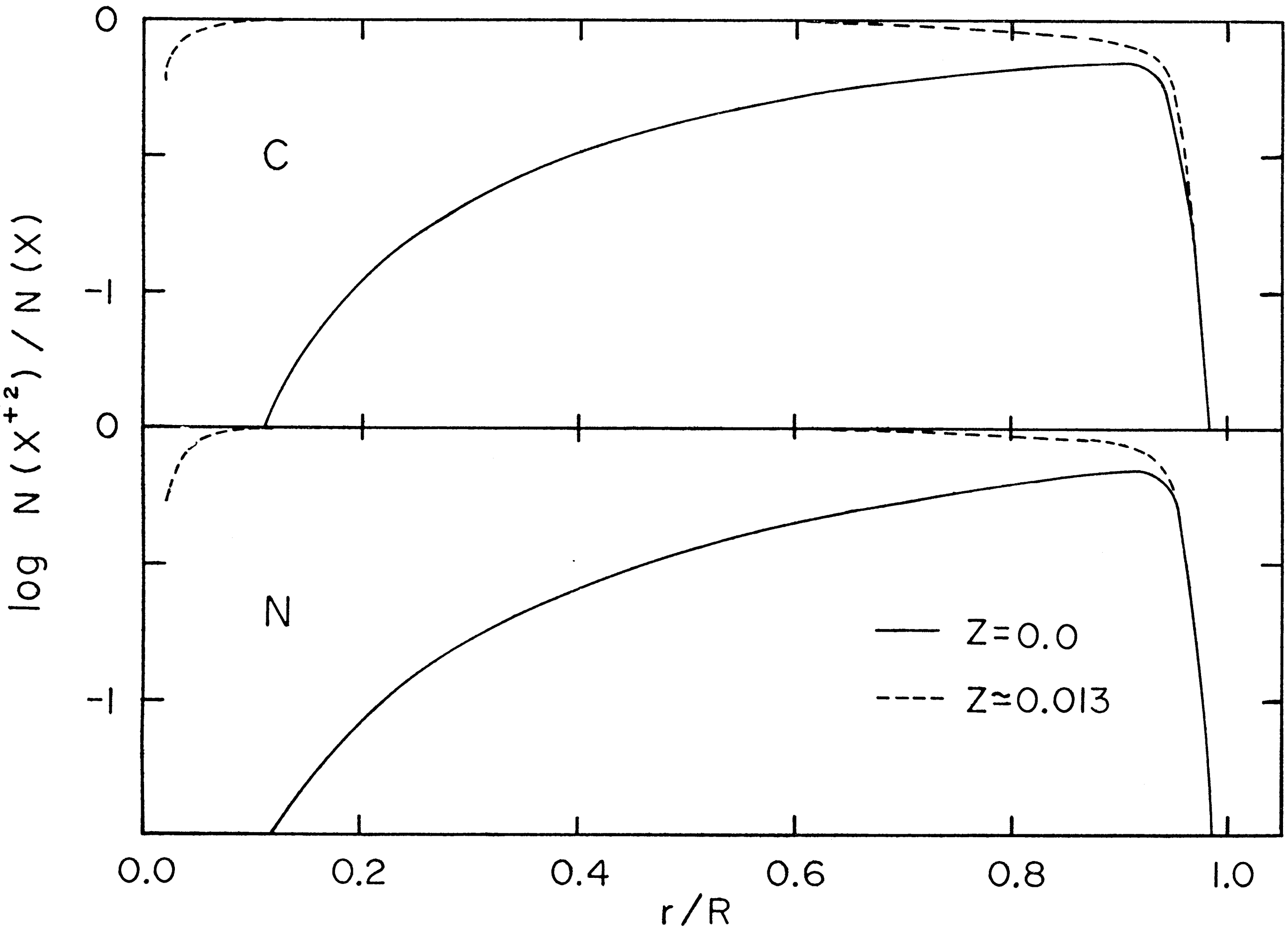

FIG. 5. Fractional abundance of C^{+2} and N^{+2} as a function of radius for Z = 0 and Z = 0.013 in the stellar atmosphere.

and infrared emission lines of [C III] at 1909Å, [N III] at 1749Å, and [N III] at 174μ.

ii) *Effects of variations in log g*

It is also very important to obtain models of the ionization structure in nebulae, taking into account variations in surface gravity, since the ultraviolet stellar flux is appreciably higher for lower gravities. Moreover, the ratio of helium-to-hydrogen ionizing photons, P(He)/P(H), also increases with decreasing gravity. These effects, as derived from the work by Mihalas (1972), are shown in Figure 6.

In the range of stellar temperatures considered we can approximately express these relations as

$$\Delta \log P(H) \sim -0.3 \, \Delta \log g$$

and (9)

$$\Delta \log P(He)/P(H) \sim -0.6 \, \Delta \log g.$$

iii) *Effects of using Non-LTE Model Atmospheres*

As already mentioned, we do not have a homogeneous set of non-LTE model atmospheres for the desired chemical compositions. In this section we will discuss the way in which we expect our results to be modified if non-LTE model atmospheres had been used. The effect of the removal of the LTE assumption is to modify in a complicated way the spectral distribution; a detailed discussion of this effect has been given by Mihalas and Auer (1970). However, since the gross characteristics of the ionization structure of hydrogen and helium are determined by the

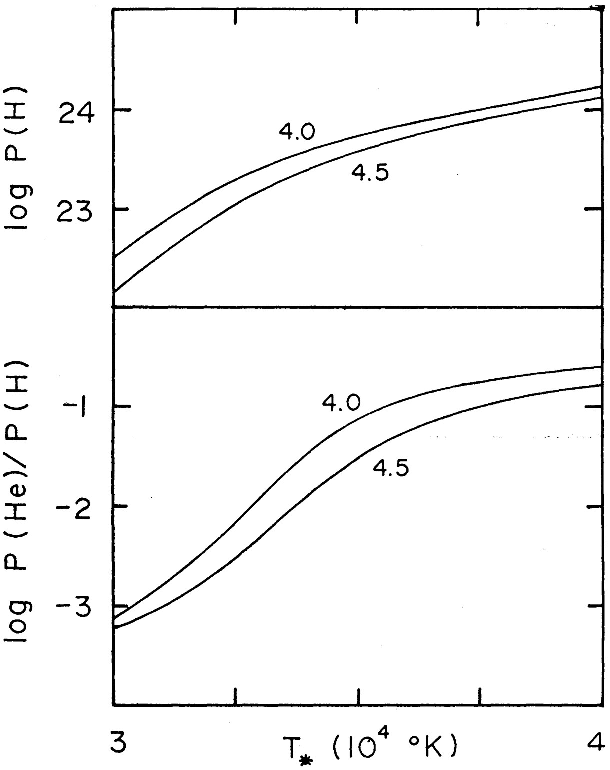

FIG. 6. Total number of ionizing photons and ratio of helium to hydrogen ionizing photons as a function of stellar temperature. Numbers on the figure correspond to log g.

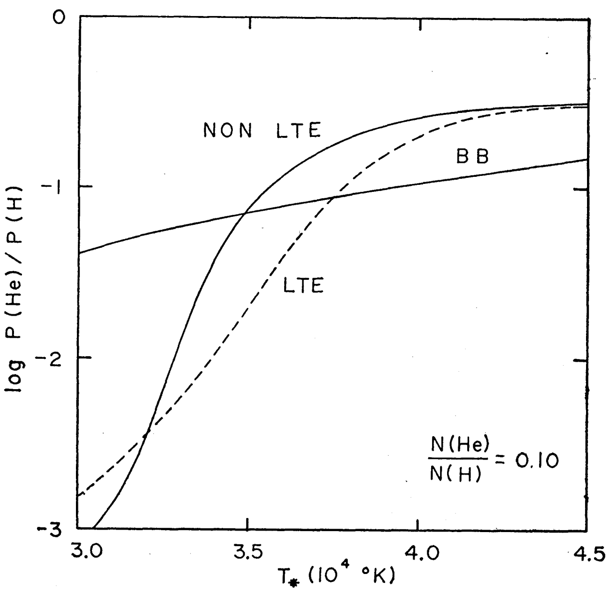

FIG. 7. Ratio of helium to hydrogen ionizing photons as a function of stellar temperature for black body radiation, LTE, and Non-LTE model atmospheres.

ratio P(He)/P(H), we will estimate the effects of non-LTE considerations on this quantity. In Figure 7 we present the dependence of P(He)/P(H) on T_* both for LTE and non-LTE models with $y = 0.10$ (Mihalas 1972). The slope for this dependence is steeper for non-LTE than for LTE models, so it is expected that the effects discussed in §IIb will appear in an even more limited range, and at lower values, of stellar temperatures.

III. MAIN SEQUENCE STARS OF DIFFERENT CHEMICAL COMPOSTIONS

In this section we examine schematically the effects on stellar luminosity and T_* due to changes in the chemical composition. On the assumption that chemical evolution takes place according to a law of $\Delta Y/\Delta Z \sim 3$, we can study the position on the H-R diagram of main sequence stars of the same mass and different initial composition. From evolutionary computations in the 12 − 20 $M_\odot$ range (Robertson 1972) we can derive approximate relations between the different initial composition and the luminosity and effective temperature

$$\frac{\partial \log L}{\partial X} = -\ 1.21, \quad \frac{\partial \log L}{\partial Z/Z} = +0.0007,$$

$$\frac{\partial \log T_*}{\partial X} = -0.009, \quad \frac{\partial \log T_*}{\partial Z/Z} = +0.0466.$$

In Figure 8 we present the changes of L and T_* due to the different composition of stars of the same

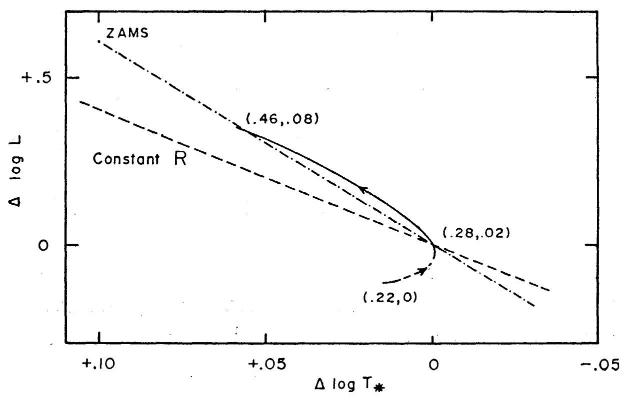

FIG. 8. Changes of L and T_* due to different composition in stars of the same mass. Numbers on the figure correspond to (Y,Z).

mass. In general for $Z \geq 0.02$ the loci of the zero age main sequences practically coincide, even though a star of the same mass is located in a different position. For $Z < 0.01$, the relations (10) may no longer be valid; nevertheless, we used them to extrapolate to lower values of Z. In the extreme case of $Z = 0$ the main sequence would be located at luminosities fainter by $\Delta \log L = -0.2$.

For a star of a given mass at $Z \geq 0.01$ an increase of the helium abundance produces a larger flux of photons more energetic than ν_1, P(H), owing to the increase of stellar effective temperature. Also the ratio P(He)/P(H) increases, since the effect of the increase in stellar effective temperature dominates that of the increase of atmospheric opacity owing to the presence of more helium atoms. The variations in P(H) and P(He)/P(H) depend on the stellar temperature. In particular, we present in Table 2 the variations of the ionizing flux for different effective temperatures.

Under the assumption of a constant IMF (initial mass function), the presence of a y gradient in the galaxies would imply an increase of the effective temperature towards the nucleus with the corresponding increase of the helium ionization degree.

IV. GRADIENTS ACROSS THE DISKS OF SPIRAL GALAXIES

From the arguments presented in §I, in addition to the N/O and N/S abundance gradients, a y gradient is also expected across the disks of spiral galaxies. In what follows we will discuss what effects the presence of a y gradient might have on the interpretation of the spectra of H II regions.

TABLE 2

DEPENDENCE OF THE IONIZING PHOTON FLUX ON THE CHEMICAL COMPOSITION FOR A STAR OF CONSTANT MASS

y	T_*	$\Delta \log P(H)$	$\Delta \log P(He)/P(H)$
0.10	30 000	0	0
0.25	34 500	1.22	0.82
0.10	35 000	0	0
0.25	40 000	0.52	0.92
0.10	40 000	0	0
0.25	46 000	0.47	0.30

Aller (1942), from the study of the spectra of H II regions in M33, found a gradient in the [O III]/Hβ intensity ratio in the sense that this ratio was smaller for H II regions closer to the nucleus. Searle (1971) found that this excitation gradient extended to other Sc galaxies and could be due to three different parameters varying towards the nuclei of galaxies; *a*) an increase in the O/H abundance ratio; *b*) an increase in the H II region dust content and *c*) a decrease in the stellar effective temperature. Searle (1971), and Searle and Sargent (1972) have given arguments in favor of possibility *a*; we think that these arguments are valid and are supported by more recent results (Benvenuti, D'Odorico and Peimbert 1973; Peimbert and Torres-Peimbert 1974). However, we do not think that the presence of an O/H abundance gradient rules out the possibility of the presence of a gradient in the dust content and/or in the stellar effective temperature of the ionizing stars.

The H II regions studied by Searle (1971) do not show a systematic change in the Hα/Hβ line intensity ratio towards the nuclei of galaxies, this is an argument againts the presence of a gradient in the dust density, at least for these objects, and for the grain particles that produce the extinction in the visual region. Moreover, Searle finds that the ratio $I(5876)/I(H\beta) \sim 0.1 \pm 0.02$ with no systematic change as a function of distance to the center. In particular, he mentions that M101#5, an inner H II region, and M101#12, an outer H II region, have practically identical helium-to-hydrogen intensity ratios. Under the assumption of no y gradient this result implies that there is no gradient in the effective temperature of the stars producing most of the ionization. However the assumption of a y gradient might imply that y^0 increases towards the nuclei of galaxies, and furthermore, from the results given in §III that the IMF of the stars producing the ionization varies in the sense that the mass of the most massive objects decreases towards the nucleus of M101. It is clear that the effect that we are looking for is not very large, consequently, high accuracy observations of the y^+ ratios in external galaxies at different distances from the galactic nuclei, and in particular near the nucleus where the effect is expected to be more pronounced, are needed to decide whether or not the IMF varies towards the nuclei of galaxies.

From detailed non-linear pulsation calculations for massive stars it has been found that there is no reason to expect an upper mass limit on the basis of pulsational instability (Larson and Starrfield 1971). Moreover Larson and Starrfield have suggested that the upper mass limit is associated, through Jeans' criterion, to the temperature in the central regions of the collapsing protostellar cloud, in the sense that for a higher temperature there corresponds a higher mass of the object. Since most of the energy losses are due to the heavy elements, it follows that the central temperature is lower because of a higher abundance of the heavy elements. If this were the dominant effects in the determination of the upper limit of stellar masses, we would expect a decrease of this upper limit towards the nuclei of galaxies. This is an argument in favor of a radial gradient of the IMF.

Churchwell, Mezger and Huchtmeier (1974) from radio observations of H II regions in our galaxy find that y^+ decreases towards the nucleus; however if uniform y prevailed this would imply that y^0 increases towards the nucleus. Moreover, they find an inverse correlation between the infrared excess and the y^+ value, and apparently this correlation is associated with the distance to the center of our galaxy. Mezger, Smith and Churchwell (1974) attribute this correlation to the presence of dust particles with the property of absorbing photons capable of ionizing helium more efficiently that those capable of ionizing hydrogen; it is clear that an IMF in which the mass of the most massive objects decreases towards the nuclei of galaxies can also explain the observations. In any case if the IMF were uniform and there were a y gradient present, then the y^0 gradient would be even steeper and the dust absorption coefficient for photons able to ionize helium would have to be even larger, with respect to the absorption coefficient for photons able to ionize hydrogen, $\sigma(\text{He})/\sigma(\text{H})$, than the values derived by Mezger *et al.*

The [S II]/Hα line intensity ratios generally increase towards the nuclei of galaxies (Peimbert 1971; Rubin and Ford 1972; Warner 1973). There are three parameters affecting this ratio: the electron temperature, the N(S)/N(H) abundance ratio and the N(S^+)/N(S) ratio. The effects due to the first two parameters counteract each other and are expected to be less important than the effect due to the third. Consequently the [S II]/Hα increase mainly corresponds to a N(S^+)/N(S) increase, which implies an increase in the y^0 value towards the nuclei of galaxies (cf. Peimbert, Rodríguez and Torres- Peimbert 1974) in agreement with the results of Churchwell *et al.* (1974) for our galaxy.

V. NUCLEUS OF OUR GALAXY

In this section we will review some observations in our galaxy and other galaxies that might provide some insight into the physical conditions prevailing in the nucleus of our galaxy. In particular, we are interested in the sources of ionization and in the chemical composition of the interstellar gas, as well as in the stellar IMF. We would like to see if it is possible to apply the results derived in §II and §III.

The nucleus of our galaxy presents a tenuous extended H II region of dimensions 1°5 × 0°5; embedded in it are four bright H II regions, G0.2 − 0.0, G0.5 − 0.0, G0.7 − 0.0 and Sgr A West. In an excellent review on this topic Mezger (1974) suggests that G0.7 − 00 and G0.5 − 00 are ionized by newly formed O stars, that the extended H II region is ionized in part by planetary nebulae and that Sgr A West is ionized by a super massive star. In what follows, we will discuss, in addition to these mechanisms horizontal branch stars and cloud colllisions as probable sources of ionization.

G0.7 − 0.0 and Sgr A West present a very good spatial and velocity correlation with the molecular clouds Sgr B2 and Sgr A, respectively. From the anomalous isotopic ratios of the latter (see §I) and the location of these four H II regions with respect to the nucleus of our galaxy we expect them to be metal-rich as well as helium-rich. In the cases of G0.2 − 0.0 and G0.7 − 0.0 there are definite upper limits to the I(He^0)/I(H^0) and I(He^+)/I(H^0) ratios, and in the case of Sag A West there is a possible detection of the I(He^0)/I(H^0) ratio (Churchwell and Mezger 1973; Huchtmeier and Batchelor 1973; Chaisson 1973; Mezger 1974).

It is well known that if the He^+ Stromgren sphere is smaller than that of H^+, detailed knowledge of the density distribution is needed to derive the y^+ value from the $I(He^0)/I(H^0)$ ratio, since there are three effects that can influence the line intensities: *a*) free-free absorption, *b*) pressure broadening and *c*) maser amplification. In the particular case in which the stars are embedded in a high density region surrounded by a more tenuous one, as is the case in the Orion Nebula, the three effects are significant at low frequencies and act in the same direction. They reduce the $I(He^0)/I(H^0)$ line ratio and consequently the line intensity ratio yields only lower limits of the y^+ value (Batchelor and Brocklehurst 1972; Brocklehurst and Seaton 1972; Churchwell, Mezger and Huchtmeier 1974). The density distribution in G0.7 − 0.0 seems to be appropriate to produce these effects (Chaisson 1973) and observations at different frequencies of the $I(He^0)/I(H^0)$ ratio or a good model of the H II region, is needed to estimate at what frequency these effects become important. In what follows we will not consider these effects, since apparently, at the frequencies at which the observations have been made, they are not very important. Under these assumptions the observations imply $y^+ + y^{++} \leq 0.03$ for G0.2 − 0.0 and G0.7 − 0.0; these values are considerably smaller than the value derived optically for all H II regions. In the case of Sgr A West the possible detection implies $y^+ \sim 0.10$.

Several astronomers have suggested that the lack of ionized helium in G0.2 − 0.0, G0.5 − 0.0 and G0.7 − 0.0, under the assumption of ionization due to OB stars, can be explained as being due to dust particles absorbing more efficiently those photons capable of ionizing helium than those capable of ionizing hydrogen (Peimbert 1973; Jura and Wright 1974; Churchwell, Mezger and Huchtmeier 1974; Cesarsky and Cesarsky 1974). Jura and Wright (1974), and Mezger *et al.* (1974) have found the required dust properties assuming a Salpeter luminosity function, $y = 0.10$ and that the infrared excess is due to the absorption of helium and hydrogen ionizing photons by dust particles; to us these hypotheses do not seem necessarily valid (see §II, §III and the following discussion).

The luminosity function in the nuclei of M31 and M81 is very different from a Salpeter luminosity function (Spinrad and Taylor 1971) in the sense that apparently most of the star formation ceased a long time ago and that very few, if any, OB stars are expected to be present. In the case of the nucleus of our galaxy it is not known if there is still a substantial rate of star formation and if this formation is characterized by an IMF similar to that of the solar neighborhood. If the luminosity function in the nucleus of our galaxy is similar to those of M31 and M81, absorption by dust particles of photons with longer wavelengths than 912 Å would contribute significantly to the observed infrared excess.

Peimbert (1968) has concluded that planetary nebulae, PN, are not responsible for the ionization in the nuclei of M51 and M81, because the degree of ionization observed in these galaxies corresponds to the early stages in the evolution of a PN when its density is, at least, an order of magnitude larger than those of the nuclei of M51 and M81. On the other hand, the degree of ionization of PN with densities similar to those of the nuclei of M51 and M81 is considerably higher than those observed in M51 and M81. On the case of the bright H II regions in the nucleus of our galaxy where a large fraction of the helium atoms is neutral, it is clear that PN are not responsible for the ionization because they would ionize, at least once, most of the helium. In the cases of Sgr A West and the extended tenuous H II region, additional information on the degree of ionization, in particular on the amount of y^{++}, is needed to decide whether or not it is possible that PN contribute significantly to the ionization. Similarly, a good knowledge of the effective temperature of the super massive stars proposed by Mezger (1974) is needed to predict the helium ionization degree.

It has been shown by Minkowski and Osterbrock (1959) that by scaling up the number of horizontal branch stars from a globular cluster to a nucleus of an elliptical galaxy, on the assumption that the luminosity function of these two types of systems are the same, there is more than enough ultraviolet radiation to explain the amount of ionized gas observed in the nuclei of elliptical galaxies. The ratio of horizontal branch to main sequence OB stars needed to explain the observed ionization is in the 100 to 1 000 range, a detailed knowledge of the stellar content in the nuclei of our galaxy is needed to ascertain the importance of this possibility.

It has also been suggested that cloud collisions might be important sources of ionization for the H II regions in the nucleus of our galaxy (Peimbert 1973; Daltabuit *et al.* 1974). One of the arguments is that cloud collisions in the 30 to 60 km s^{-1} range are capable of ionizing most of the hydrogen while helium remains mostly neutral. There is a large body of evidence in favor of anomalous velocities in many nuclei of galaxies, but we will restrict the discussion to the nuclei of some normal galaxies and our own.

The [O I]/[O II] and [O I]/[O III] line intensity ratios observed in the nuclei of M51 and M81 (Peimbert 1968) are very large in comparison with those of normal high density H II regions ionized by OB stars. The [O I] lines must originate in partially ionized H II regions (Peimbert 1971). The partial ionization can be simply explained by cloud collisions. This argument by itself does not prove that cloud collisions are responsible for the [O I] line intensities in the nuclei of M51 and M81.

Non-circular motions, consisting of expansion in the interstellar gas, have been reported for M31 and M81 (Rubin and Ford 1971; Goad 1974). In the case of M31 they are as large as 100 km s^{-1} in some directions.

From observations of molecular clouds in the direction of the galactic center Kaifu, Kato and Iguchi (1972) and Scoville (1972) have suggested the existence of a ring of molecular clouds expanding (or contracting) with a velocity of about 140 km s^{-1}, a mass of about 3×10^6 $M_\odot$, an energy of about 6×10^{53} erg and a radius of about 200 to 300 pc. This expansion might be the product of an explosion in the center of the galaxy about 10^6 years ago. According to Mezger the ionization rate in the extended nuclear region of $1^\circ\!.5 \times 0^\circ\!.5$ is about 3×10^{52} s^{-1} or $\sim 7 \times 10^{41}$ ergs s^{-1}. If the kinetic energy were used to ionize this region it would dissipate in about 3×10^4 years, which clearly is a time interval too short to account for all the observed ionization as being due to cloud collisions. However, the mass as well as the kinetic energy involved in the expansion might be higher, and the mechanism responsible for the non-circular motions might be providing energy to the system in a shorter time scale than 10^6 years.

Moreover, the velocity dispersion of G0.7 − 0.0 amounts to about 40 km s^{-1} and is considerably higher than in normal H II regions; on the other hand the velocity dispersion of G0.5 − 0.0 appears to be normal (Chaisson 1973). In the case of Sgr A West the conditions are even more favorable for cloud collisions than in the case of G0.7 − 0.0, since the observed velocity dispersion is of the order of 200 km s^{-1} which might be due to large scale or turbulent motions (Mezger 1974).

It is clear from the discussion in this section that it would be premature to use the results derived in §II and §III to study the nucleus of our galaxy. However, these results might be used in the near future when more observations become available, in particular, high accuracy determinations of line intensity ratios in and near the nuclei of galaxies.

REFERENCES

Aller, L. H. 1942, *Ap. J.*, **95**, 52.
Aller, L. H., Menzel, D. H. and Pekeris, C. L. 1939, *Ap. J.*, **90**, 601.
Batchelor, A.S.J. and Brocklehurst, M. 1972, *Astrophys. Lett.*, **11**, 129.
Benvenuti, P., D' Odorico, S. and Peimbert, M. 1973, *Astron. and Astrophys.*, **28**, 447.
Bertojo, M., Chui, M. F. and Townes, C. H. 1974, *Science*, **184**, 619.
Brocklehurst, M. and Seaton, M. J. 1972, *M.N.R.A.S.*, **157**, 179.
Cesarsky, C. J. and Cesarsky, D. A. 1974, private communication.
Chaisson, E. J. 1973, *Ap. J.*, **186**, 555.
Churchwell, E. B. and Mezger, P. G. 1973, *Nature*, **242**, 319.
Churchwell, E. B., Mezger, P. G. and Huchtmeier, W. 1974, *Astron. and Astrophys.*, **32**, 283.
Daltabuit, E., Andrade, J., Cantó J. and Peimbert, M. 1974, *Rev. Mex. Astron. Astrofis.*, **1**, 203.
Goad, J. W. 1974, *Ap. J.*, **192**, 311.
Huchtmeier, W. and Batchelor, R. A. 1973, *Nature*, **243**, 155.
Hummer, D. G. and Mihalas, D. 1970, *M.N.R.A.S.*, **147**, 339.
Jura, M. and Wright, E. L. 1974, *Ap. J.*, **188**, 473.
Kaifu, N., Kato, T. and Iguchi, T. 1972, *Nature Phys. Sci.*, **238**, 105.
Larson, R. B. and Starrfield, S. 1971, *Astron. and Astrophys.*, **13**, 190.
Mc Clure, R. D. 1969, *A. J.*, **74**, 50.
Mezger, P. G. 1974, in *ESO/SRC/CERN Conference on Research Programs for the New Large Telescopes*, ed. A. Reiz (held at Geneve, Switzerland), p. 97.
Mezger, P. G., Smith, L. F. and Churchwell, E. 1974, *Astron. and Astrophys.*, **32**, 269.
Mihalas, D. 1965, *Ap. J. Supp.*, **9**, 321.
Mihalas, D. 1972, *NCAR Technical Note No. NCAR-TN/*

STR--76 (Boulder: National Center for Atmospheric Research).

Mihalas, D. and Auer, L. H. 1970, *Ap. J.*, **160**, 1161.

Minkowski, R. and Osterbrock, D. E. 1959, *Ap. J.*, **129**, 583.

Peimbert, M. 1968, *Ap. J.*, **154**, 33.

Peimbert, M. 1971, *Bol. Obs. Tonantzintla y Tacubaya*, **6**, 97.

Peimbert, M. 1973, in *The Formation and Dynamics of Galaxies, I.A.U. Symposium 58*, ed. J. R. Shakeshaft, (Dordrecht: D. Reidel), in press.

Peimbert, M. 1975, *Ann. Rev. Astron. Ap.*, **13**, in press.

Peimbert, M. and Torres-Peimbert, S. 1974, *Ap. J.*, **193**, 327.

Peimbert, M., Rodríguez, L. F. and Torres-Peimbert, S. 1974, *Rev. Mex. Astron. Astrof.*, **1**, 129.

Robertson, J. W. 1972, *Ap. J.*, **177**, 473.

Rubin, V. C. and Ford, W. K. Jr. 1972, in *External Galaxies and Quasi-Stellar Objects, I.A.U. Symposium 44*, ed. D. E. Evans (Dordrecht: D. Reidel), p. 49.

Scoville, N. Z. 1972, *Ap. J. Letters*, **175**, L127.

Searle, L. 1971, *Ap. J.*, **168**, 327.

Searle, L. and Sargent, W. L. W. 1972, *Ap. J.*, **173**, 25.

Spinrad, H. and Taylor, B. J. 1971, *Ap. J. Suppl.* **22**, 445.

Spinrad, H., Gunn, J. E., Taylor, B. J., Mc Clure, R. D. and Young, J. W. 1971, *Ap. J.*, **164**, 11.

Spinrad, H., Smith, H. E. and Taylor, B. J. 1972, *Ap. J.*, **175**, 649.

Torres-Peimbert, S. and Peimbert, M. 1971, *Bol. Obs. Tonantzintla y Tacubaya*, **6**, 101.

Warner, J. W. 1973, *Ap. J.*, **186**, 21.

Wollman, E. R. 1973, *Ap. J.*, **184**, 773.