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OBSERVATIONS OF FAINT H II REGIONS IN OUR GALAXY

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RESUMEN

En este trabajo se presentan observaciones fotoeléctricas de regiones H II débiles, con medida de emisión menor que 500 cm^{-6} pc en la línea Hα. A partir de estas observaciones se obtiene que el brillo superficial límite en Hα, para la detección de una región H II en las placas rojas de Palomar, es menor que 2.75×10^{-6} erg cm^{-2} sr^{-1}. Comparando las observaciones de Reynolds *et al.* (1974) con las placas rojas de Palomar se obtiene que el valor límite se encuentra entre 2.5×10^{-6} y 5.5×10^{-6} erg cm^{-2} s^{-1} sr^{-1}, lo cual corresponde a una medida de emisión entre 17 y 40 cm^{-6} pc, para una nebulosa no enrojecida con $T_e = 6000$ °K.

Se hace un estudio del mecanismo de ionización y de la composición química de dos de las regiones observadas, pertenecientes a la Nebulosa del Arco de Barnard y que están a 4.5° de la Nebulosa de Orión. Se encuentra que las abundancias relativas de nitrógeno, oxígeno e hidrógeno no son las mismas para ambas nebulosas. Se presentan algunos argumentos en favor de una abundancia normal de nitrógeno en el Arco de Barnard. Suponiendo que el cociente de abundancia de nitrógeno a hidrógeno es el mismo en esta nebulosa y en la de Orión se obtiene para el Arco de Barnard una deficiencia de oxígeno de un factor entre 2 y 4 relativa a Orión, y una temperatura electrónica entre 6000 y 7000 °K.

ABSTRACT

We present photoelectric observations of faint H II regions of emission measure lower than 500 cm^{-6} pc at Hα. From these observations it is found that the limiting surface brightness in Hα for detection of an H II region in the Red Palomar Sky Survey is smaller than 2.75×10^{-6} erg cm^{-2} s^{-1} sr^{-1}. By comparing the observations by Reynolds *et al.* (1974) with the Red PSS we find that the limiting value lies in the 2.5×10^{-6} to 5.5×10^{-6} erg cm^{-2} s^{-1} sr^{-1} range which for an unreddened nebula at $T_e = 6000$ °K corresponds to an emission measure between 17 and 40 cm^{-6} pc.

The mechanism of ionization and the chemical abundances of two of the observed regions, beloging to the Barnard Loop Nebula and located about 4.5° away from the Orion Nebula, are studied. It is found that the relative abundances of N, O and H are not the same in both nebulae. Some arguments are given in favor of a normal nitrogen abundance for the Barnard Loop. By assuming that in this object the nitrogen to hydrogen abundance ratio is the same as for the Orion Nebula we derive an electron temperature in the 6000 — 7000 °K range as well as an oxygen underabundance of a factor of 2 to 4.

Key words: ABUNDANCES, NEBULAR — INTERSTELLAR MATTER — NEBULAE.

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I. INTRODUCTION

The observations of faint H II regions can lead us to a better understanding of the interstellar medium in our galaxy. In this paper we are interested in two problems: to derive the minimum surface brightness at Hα for an H II region to be observable on the red prints of the National Geographic Society —Palomar Observatory Sky Atlas (RPSS), and to study the chemical composition of faint H II regions in the solar neighborhood.

The limiting surface brightness of the RPSS, $S(H\alpha)_{min}$, is of interest for the users of these plates in particular, for the study of the energy input to the interstellar medium (cf. Torres-Peimbert *et al.* 1974). This problem has been studied previously by Poveda (1963) who, from photographic data obtained by other authors, estimated that the minimum emission measure for a nebula to be observable in Hα is of approximately 50 cm^{-6} pc.

The chemical abundances of the most abundant elements such as O, N, and S in the sun and the Orion Nebula are similar (Peimbert and Costero 1969); alternatively, in regions of low density the *Copernicus* satellite observations (Morton *et al.* 1973) indicate underabundances of about one order of magnitude for Mg, P, Cl and Mn as well as of about one half, to one, order of magnitude in O. Therefore we would like to find out whether or not the abundances relative to hydrogen of the most abundant heavy elements in the faint H II regions are deficient relative to that of the Orion Nebula. This type of information might be important in the study of formation and destruction of molecules and dust grains.

II. OBSERVATIONS

The observations were obtained at Cerro Tololo Inter-American observatory from 1974 December 7 to 10 with the 60-inch telescope and the Harvard scanner. The observational procedure was identical to that described by Peimbert and Torres-Peimbert (1974). The entrance slits used correspond to 5″2 × 77″6 on the plane of the sky and were oriented east-west. The identifications of the sixteen observed regions are presented in Table 1. Regions R1a, R1b, R2a, and R2b were chosen because they do not show any nebulosity in the RPSS, they are far away from the galactic plane, and according to Reynolds *et al.* (1974) the general area has a very low surface brightness at Hα. Our observations of regions R1a to R2b were used to evaluate nightly the sky contribution to the observed intensities; in particular to our λ6563 measurements which include the geocoronal Hα and other telluric emission lines. Regions R3a to R8b were chosen because they show from faint to very faint nebulosity in the RPSS, presumably due to Hα emission. In all objects we observed the following wavelenghts: λλ6300, 6364, 6400, 6496, 6563, 6584, 6620 and 6726. The exit slit corresponds

TABLE 1

LOCATION OF OBSERVED REGIONS*

Region	Reference Star					Coordinates Relative to Reference Star	
	HD	α (1950)	δ (1950)	l	b	Δα	Δδ
R1a	16060	2h32m25s	+07°15′17″	162°7	−47°5	+15′	+00′
R2a	17791	2 48 45	+01 58 05	172.5	−48.8	+15	+00
R3a	18509	2 56 02	+01 55 18	174.3	−47.6	+30	+00
R4a	25621	4 01 33	+02 41 33	187.5	−34.5	−35	+06
R5a	26373	4 07 43	+01 12 01	190.7	−34.4	+40	+00
R6a	26739	4 11 06	−01 16 33	193.4	−34.7	+07	+03
R7a	39291†	5 48 57	−07 31 48	212.3	−16.7	−03	+10
R8a	39647	5 51 15	−05 42 50	210.9	−14.9	+05	−25

* Regions b are located 168″ west of regions a.

† 55 Ori

to 20Å for these wavelengths; the observations at λλ6400 and 6620 were used to estimate the continuum contribution, mainly due to starlight, and the observations at λλ6300, 6364 and 6496 were used to estimate the night sky emission. The observations were carried out as close to the meridian as possible and in all cases at hour angles smaller than 1^h30^m to minimize the effect of night sky emission. The Hα surface brightness, S(Hα), derived from our observations is presented in Table 2. Each region was observed at least in two different nights; the errors in log S(Hα) are smaller than 0.08 and were estimated from photon statistics and the variations from night to night. We did not detect Hα in regions R3a, R3b, R5a and R5b, and consequently we present only upper limits.

TABLE 2

OBSERVED SURFACE BRIGHTNESS

Region	log S(α) (erg cm^{-2} s^{-1} sr^{-1})	EM (cm^{-6} pc)	Source*
R3a	<-5.29	<4.0 (1)	1
R3b	<-5.22	<4.7 (1)	1
R4a	-4.85	1.10 (2)	1
R4b	-4.77	1.32 (2)	1
R5a	<-5.29	<4.0 (1)	1
R5b	<-5.22	<4.7 (1)	1
R6a	-5.49	2.5 (1)	1
R6b	-5.61	1.9 (1)	1
R7a	-4.35	3.47 (2)	1
R7b	-4.30	3.89 (2)	1
R8a	-4.22	4.68 (2)	1
R8b	-4.27	4.17 (2)	1
Ori I	-0.94	1.44 (6)	2, 3
Ori III	-1.26	6.12 (5)	2, 3
Ori IV	-2.28	5.00 (4)	2, 3
M8 I	-1.91	1.44 (5)	2
M8 VI	-3.14	7.52 (3)	2

* Source. (1) This paper, (2) Peimbert and Costero 1969, (3) Costero and Peimbert 1970

In all objects where Hα was detected the nebular line emissions at λλ6584 and 6726 were considerably fainter than Hα; for all regions, excepting R7a and R7b, these line intensities had errors larger than 0.08 in the logarithm and are not presented here. In Table 3 we present absolute line intensities for the relatively bright regions R7a and R7b; in this table the errors in the intensity ratios are smaller than 0.08 in the logarithm.

TABLE 3

LINE INTENSITIES*

λ	Ion	R7a	R7b
3727	[O II]	-0.26	-0.19
4861	Hβ	0.00	0.00
5007	[O III]	<-0.64	<-0.68
6563	Hα	$+0.42$	$+0.43$
6584	[N II]	-0.13	-0.20
6717 + 6731	[S II]	-0.08	-0.12

* Given in log F(λ)/F(Hβ)

III. MINIMUM SURFACE BRIGHTNESS AT Hα DETECTABLE ON THE RPSS

The surface brightness at Hα of a gaseous nebula is given by

$$S(\mathrm{H}\alpha) = 10^{-0.4A(\mathrm{H}\alpha)}\, \mathcal{J}(\mathrm{H}\alpha)\ \mathrm{erg\ cm^{-2}\ s^{-1}\ sr^{-1}}, \qquad (1)$$

where A(Hα) is the interstellar absorption at Hα, in magnitudes, and $\mathcal{J}$(Hα) is the intrinsic surface brightness given by

$$\mathcal{J}(\mathrm{H}\alpha) = \frac{1}{4\pi}\int N(\mathrm{H}^+)N_e\,\alpha(3\rightarrow 2)\,h\nu_{(3\rightarrow 2)}\,dl \qquad \mathrm{erg\ cm^{-2}\ s^{-1}\ sr^{-1}}, \qquad (2)$$

where $\alpha(3\rightarrow 2)$ is the Hα effective recombination coefficient. Sometimes it is convenient to express the surface brightness of an object in terms of the emission measure defined by

$$\mathrm{EM} = \int N(\mathrm{H}^+)N_e\,dl\ \mathrm{cm^{-6}\ pc}; \qquad (3)$$

which from equation (2) can be written as

$$\mathrm{EM} = 2.41\times 10^3\,T^{0.92}\,\mathcal{J}(\mathrm{H}\alpha)\ \mathrm{cm^{-6}\ pc}, \qquad (4)$$

where $\alpha(3\rightarrow 2)$ has been taken from Brocklehurst (1971) interpolated in the 5 000 to 10 000°K temperature range.

In Table 2 we present the emission measure corresponding to the observed H II regions. The EM of regions R3a to R8b was computed under the assumption that $T_e = 6\,500°K$ and that the total absorption at Hα is negligible (see §IV). For comparison we also present in Table 2 S(Hα) and EM for other H II regions. The emission measure for Orion and M8 were computed from the results by Peimbert and Costero (1969), with the exception of A(Hα) for the Orion Nebula for which the results by Costero and Peimbert (1970) were used.

Under the assumption that the RPSS is comprised by a homogeneous set of plates, and from the values in Table 2 it follows that the minimum log S(Hα) for detection in the RPSS is smaller than -5.56, the average value for R6a and R6b.

In what follows we will discuss the homogeneity of the RPSS set regarding Hα emission. The background illumination of the RPSS is in general not dominated by Hα; $S(H\alpha)_{min}$ is considerably lower than the surface brightness due to the night sky, S(NS). The spectral sensitivity at Hα of the 103a-E emulsion in combination with filter 2444 of red plexiglass is similar to that at the λλ6300 and 6364 lines. According to Allen (1973), a typical value for the night sky surface brightness at λ6300 is 150 rayleigh which corresponds to $\log S(6300) = -4.42$; *i.e.,* at least a factor of ten larger than $S(H\alpha)_{min}$. From our observations we detected variations in the night sky emission. In particular, the [O I] 6300Å night sky line intensity varied by almost a factor of ten in the range of $\log S(6300) = -5.30$ to -4.35 (20 to 180 rayleigh). For three of the nights the intensity values were $\log S(6300) \sim -4.5$ while for the fourth they were $\log S(6300) \sim -5.1$. The variation in a single night reached values as large as a factor of two. It is well known that not only the λ6300 line intensity is variable but that the background intensity of the RPSS varies by as much as a factor of three (Minkowski and Abell 1963). This variation might be partially responsible for the non-uniformity of $S(H\alpha)_{min}$ from plate to plate.

There have been several studies of the faint Hα emission in our galaxy (cf. Sivan 1974). The most useful one to estimate $S(H\alpha)_{min}$ is that by Reynolds *et al.* (1974) who have prepared an excellent Hα emission contour map covering the range of log S(Hα) from -6.27 to -4.57; the map is based on 338 discrete observations corresponding to a circular beam size of 6′.5 and separated by several degrees. We located 216 of their points in the RPSS to examine whether or not they correspond to detectable nebulosity. The points in the $100° \leq l \leq 160°$ range were not used by us since Reynolds *et al.* did not present the contribution to their surface brightness due to the Perseus arm. The results are presented in Figure 1. The fraction of points inside H II regions was plotted for each of the contour intervals given by Reynolds *et al.* From this figure it is found that in general background nebulosity of $S(H\alpha) < 2.5 \times 10^{-6}$ erg cm^{-2} s^{-1} sr^{-1} is not detectable on the RPSS, while nebulosity of $S(H\alpha) > 5.5 \times 10^{-6}$ erg cm^{-2} s^{-1} sr^{-1} can be detected. That is, $\log S(H\alpha)_{min}$ lies between -5.61 and -5.26; which, under the assumptions of $A(H\alpha) = 0$, and $T_e = 6\,000°K$ (the temperature adopted by Reynolds *et al.*), corresponds to EM between 17 and 40 cm^{-6} pc, respectively.

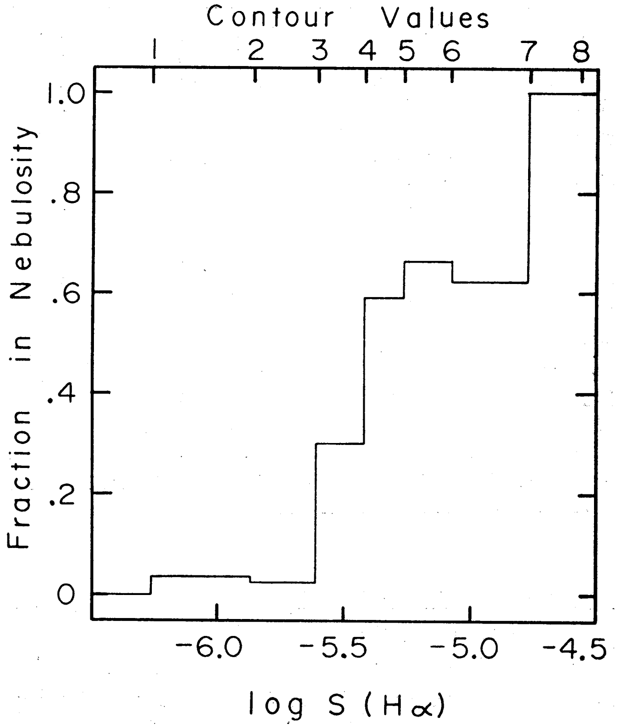

FIG. 1. Fraction of observed points by Reynolds *et al.* (1974) that are inside detectable nebulosity in the RPSS, for each of the nine contour intervals defined by them. The equivalent surface brightness corresponding to each contour value is also given.

Probably this range in the $S(H\alpha)_{min}$ value is due to the inhomogeneity of the RPSS.

The $S(H\alpha)_{min}$ value derived here is in good agreement with the estimate by Poveda (1963). Part of the difference in the EM derived by us with respect to that derived by Poveda is due to the adopted temperatures.

IV. ON THE BARNARD LOOP NEBULA

The Barnard Loop Nebula is an extended faint H II region covering a large region of the sky of approximately 14 degrees in diameter. Hα pictures of the entire object are presented by O'Dell *et al.* (1967) and Isobe (1973). O'Dell *et al.* based on observations of the continuum ultraviolet emission have made a model with the following characteristics: a) the total atomic density distribution increases outward; b) most of the low density material, that is inside the boundaries of the Barnard Loop Nebula, is ionized; and c) there is an external neutral shell expanding with a velocity of 9 km s^{-1}, which is the observed velocity of expansion from a 21 cm study of the general area carried out by Menon (1958). O'Dell *et al.* suggest that the density distribution might be the result of an outward radial force due to stellar radiation pressure acting on the grains mixed with the gas. Furthermore, they suggest that, since the density of the region is similar to that of an average region of the interstellar medium, this object is probably a phenomenon created in the interstellar medium by the presence of the early type stars of the Orion complex.

Regions R7a, R7b, R8a and R8b form part of the Barnard Loop Nebula, therefore it is expected that the mechanism responsible for the ionization of the nebula applies to these regions. Moreover, the study of the emission line intensities of the Barnard Loop Nebula might provide some clues on the chemical composition of the low density interstellar medium.

a) Ionization

We will discuss the observations of regions R7a and R7b presented in Table 3. By comparing the observed Hα/Hβ ratio with the theoretical one predicted by Brocklehurst (1971) it follows that the reddening is negligible. Consequently no reddening correction was applied to the observations. The reddening corresponding to 55 Ori, a star very close to regions R7a and R7b (see Tables 1 and 4), is $E(B-V) = 0.04$, in agreement with the result derived from the emission line intensities. Moreover Isobe (1973) finds from star counts in the regions of the Orion complex that the extinction is also very small.

The very low upper limits to the $I(5007)/I(H\beta)$ ratios rule out X rays and cosmic rays as responsible for most of the ionization in the directions of R7a and R7b (Bergeron and Souffrin 1971). It can also be shown that shock waves are not responsible for the ionization of the Barnard Loop because they would dissipate the small velocity of expansion in a very short time scale. Furthermore, according to the computations by Daltabuit *et al.* (1974) the velocity of expansion is not high enough to produce appreciable ionization. Therefore it is expected that most of the ionization of the Barnard Loop should be due to OB stars of the Orion region.

A crude representation of the brightest part of the Barnard Loop Nebula will be adopted to estimate the number of photons needed to ionize it. This representation consists of a semicircular band with an outer diameter of 14° and an inner diameter of 12° with an average surface brightness $\log S(H\alpha) = -4.35$, estimated from the four observed regions. The rate of stellar Lyman continuum photons needed to keep the nebula ionized is given by

$$L_H = 4\pi d^2 S(H\alpha)\, \Omega \frac{\alpha_B}{\alpha(3 \rightarrow 2)} \frac{1}{h\nu_{3\rightarrow 2}} \qquad (5)$$

where d is the distance, Ω the solid angle, α_B the hydrogen recombination coefficient to all levels but the first, and $\alpha(3 \rightarrow 2)$ is the Hα effective recombination coefficient. By adopting a distance of 450 pc which corresponds to the Orion Nebula (Osterbrock and Flather 1959) and the α's given by Osterbrock (1974) and Brocklehurst (1971), interpolated for $T_e = 6\,500°K$ (see §III*b*), it is found that $L_H = 4.7 \times 10^{48}$ photon s^{-1}.

In Table 4 we list the OB stars with moderate and low reddening responsible for most of the stellar Lyman continuum photons of the Orion complex. The spectral types as well as the L_H values were

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obtained from Cruz-González *et al.* (1974), Hoffleit (1964) and Torres-Peimbert *et al.* (1974), with the exception of the spectral type of θ^1 Ori C which was obtained from Conti and Alschuler (1971). The distances to these objects were estimated by assuming the normal reddening law with the exception of θ^1 Ori C and θ^2 Ori for which a value of $A_V/E(B-V) = 5.5$ was adopted (Costero and Peimbert 1970). The distance to the Orion Nebula is not well known, the value given by Osterbrock and Flather (1959) is a mean between the value of 500 pc derived by Sharpless (1952) and that of 400 pc by Johnson and Hiltner (1956). A simple average of the stellar distances given in Table 4 yields $\langle d \rangle = 424$ pc, in closer agreement with the value by Johnson and Hiltner. The total value of L_H for all the stars in Table 4 is 3.8×10^{49} photon s^{-1}. Considering the uncertainties in the stellar atmosphere models and in the spectral classification, for some objects errors as large as a factor of 2 in L_H are to be expected. On the other hand, the agreement of the stellar distances of Table 4 indicates that the adopted luminosities are not seriously in error. In what follows we will try to ascertain whether or not it is possible that some of the ionizing photons produced by these stars reach the Barnard Loop Nebula. One of the main uncertainties in this estimate is due to the unknown amount of dust and its UV absorbing properties around and between the stars and the Loop.

TABLE 4

ULTRAVIOLET FLUXES AND DISTANCES CORRESPONDING TO OB STARS NEAR THE BARNARD LOOP

Star	m_V	B-V	Spectral Type	distance (pc)	L_H (phot s^{-1})
δ Ori*	2.20	−0.21	O9.5 I	532	1.1 (49)
θ^1 Ori C	5.13	+0.03	O6.7 V	417	8.0 (48)
θ^2 Ori	5.07	−0.10	O9.0 V	439	1.8 (48)
ι Ori	3.00	−0.25	O8.5 III	461	5.3 (48)
ε Ori	1.70	−0.19	B0 Ia	431	2.8 (48)
σ Ori	3.90	−0.24	O9.5 V	384	1.0 (48)
ζ Ori†	1.88	−0.21	O9.7 Ib	316	5.7 (48)
ζ Ori‡	4.10	...	O9.5 IV	461	1.8 (48)
κ Ori	2.04	−0.18	B0.5 Ie	444	1.7 (47)
55 Ori	5.35	−0.20	B2 V	351	2.8 (44)

* HD 36486
† HD 37742
‡ HD 37743

It is well known that in some directions the Orion Nebula is ionization bounded; however in other directions this might not be the case since lines of relatively high degree of ionization, i.e. [O III], extend to the boundary (Wurm and Rosino 1959; Reitmeyer 1965). Consequently it is possible that a fraction of the Lyman photons corresponding to θ^1 Ori C and θ^2 Ori escape from the Orion Nebula. Another argument in favor of this idea was provided by Menon (1962) who found that the number of Lyman continuum photons produced by θ^1 Ori C and θ^2 Ori is approximately a factor of three higher than the number needed to keep the nebula ionized.

We will repeat here the computation by Menon (1962), mainly because the spectral type for θ^1 Ori C adopted by us is later than that adopted by him. The thermal radio radiation received from an optically thin isothermal homogeneous sphere in erg cm^{-2} s^{-1} Hz^{-1} is given by (Minkowski 1968).

$$I_\nu = \frac{r_0^{\,3}}{3d^2} N_e\,(\mathrm{rms})\; N_i\,(\mathrm{rms})\; 3.75 \times 10^{-38}\, T_e^{-1/2} \left(17.74 + \ln \frac{T_e}{\nu}\right)^{3/2}; \tag{6}$$

while the total rate of Lyman continuum photons needed to maintain the Orion Nebula ionized is given by

$$L_H = \frac{4}{3}\pi r_0^{\,3}\, Ne(\mathrm{rms})\, N_p(\mathrm{rms})\, \alpha_B. \tag{7}$$

Menon (1961) has derived a model for the Orion Nebula from which it follows that for $\nu = 1 \times 10^{10}$ Hz it is optically thin. Therefore, by adopting d = 450 pc, $N_p(\mathrm{rms})/N_i(\mathrm{rms}) = 0.94$ (Peimbert and Costero 1969), $I_\nu = 3.9 \times 10^{-21}$ erg cm^{-2} s^{-1} Hz^{-1} for $\nu = 9.4 \times 10^9$ Hz (which is the average value from the eight measurements in the $9.375 - 9.5 \times 10^9$ Hz range by Howard and Maran 1965) and equations (6) and (7) we obtain $L_H = 7.8 \times 10^{48}$ photon s^{-1} for the Orion Nebula. From Table 4 it can be seen that the number of ionizing photons produced by θ^1 Ori C and θ^2 Ori is 1.3 times larger than the number needed to maintain the Orion Nebula ionized; the number of ionizing photons produced by θ^1 Ori C would be even larger if an earlier spectral type were adopted for this star. In addition to those photons escaping from the Orion Nebula some of the other stars listed in Table 4 might be providing photons that reach and ionize the Barnard Loop Nebula; a very likely candidate is ι Ori which is not surrounded by dense gaseous clouds.

From the values in Table 4 it can be shown that the contribution of 55 Ori to the ionization of the regions comprising R7a and R7b is negligible; on the other hand, ι Ori and κ Ori might contribute appreciably to the ionization of these regions. The low upper limits for the I(5007)/I(Hβ) ratios are in agreement with this hypothesis since the spectral types and the dilution factor correspond to a very low oxygen ionization degree.

b) *Density and Mass*

To estimate the electron density and the mass of the Barnard Loop Nebula we will assume that it is shaped like a section of a cylindrical shell, of depth along the line of sight equal to its diameter, and with the surface dimensions specified previously (§III*a*). From this configuration, assuming that ionization equilibrium prevails (equation 7), that helium is neutral, and that the photon flux is the one derived from the surface brightness ($L_H = 4.7 \times 10^{48}$ phot s^{-1}) we obtain $N_e(\text{rms}) = 1.8$ cm^{-3}.

By assuming that N(He)/N(H) = 0.1, a mass of $M(\text{rms}) = 9 \times 10^3\ M_\odot$ is derived. Very similar results are obtained if a spherical shell is adopted. In the presence of density fluctuations this determination becomes an upper limit to the mass of the object (cf. Peimbert 1968).

c) *Chemical Abundances*

From the intensity ratios of forbidden lines of heavy elements to Hβ it is possible to obtain the abundances of the different ions relative to H$^+$ assuming different electron temperatures. From the very low electron density derived in §III*b*, it follows that in general collisional de-excitation is not important, and that the equations for the relative abundances given by Peimbert and Torres-Peimbert (1971) can be approximated by:

$$\frac{N(O^{++})}{N(H^+)} = 4.14 \times 10^{-5}\, T^{-0.34} \frac{I(5007)}{I(H\beta)} \exp\,(2.89 \times 10^4/T_e), \tag{8}$$

$$\frac{N(O^{+})}{N(H^+)} = 1.72 \times 10^{-5}\, T^{-0.34} \frac{I(3727)}{I(H\beta)} \exp\,(3.86 \times 10^4/T_e), \tag{9}$$

$$\frac{N(N^{+})}{N(H^+)} = 4.16 \times 10^{-5}\, T^{-0.34} \frac{I(6584)}{I(H\beta)} \exp\,(2.2 \times 10^4/T_e). \tag{10}$$

Moreover, the very low upper limits for the λ5007/Hβ line intensity ratio in R7a and R7b imply that most of the oxygen is singly ionized. Considering the similar ionization potentials of nitrogen and oxygen as well as theoretical ionization structure models of H II regions ionized by OB stars (cf. Peimbert *et al.* 1974), it is expected that most of the nitrogen will be also singly ionized. Consequently, to a very good approximation the following expressions are valid

$$\frac{N(O)}{N(H)} = \frac{N(O^+)}{N(H^+)} \tag{11}$$

and

$$\frac{N(N)}{N(H)} = \frac{N(N^+)}{N(H^+)}, \tag{12}$$

in regions R7a and R7b.

From expressions (9) to (12) and the line intensities of Table 3 the N/H, O/H and N/O abundance ratios relative to those of the Orion Nebula (Peimbert and Costero 1969) can be obtained as a function of temperature. These results are presented in Figure 2 for R7a and in Table 5 for R7a and R7b.

The three abundance ratios that can be formed with oxygen, nitrogen and hydrogen depend on the electron temperature and the emission line intensities. Since the emission lines due to O$^+$, N$^+$ and H$^+$

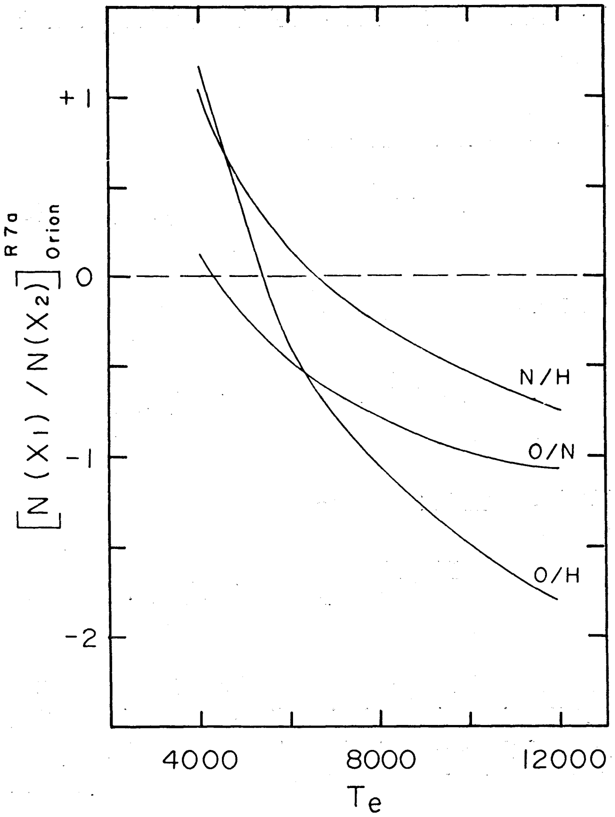

Fig. 2. Temperature dependence of the logarithmic abundance ratios relative to the Orion Nebula for region R7a, as derived from the observed values.

TABLE 5

ELECTRON TEMPERATURES AND CHEMICAL ABUNDANCES*

Region	Te (°K)	N(O)/N(H)	N(N)/N(H)	N(O)/N(N)
R7a	4300	7.08	7.08	1.00
	5500	1.00	2.24	0.45
	6700	0.26	1.00	0.26
	9000	0.051	0.39	0.13
	12000	0.017	0.19	0.09
R7b	4800	3.55	3.55	1.00
	5600	1.00	1.78	0.56
	6300	0.43	1.00	0.43
	9000	0.038	0.25	0.15
	12000	0.019	0.16	0.12

* All abundance ratios are given relative to the Orion Nebula (Peimbert and Costero 1969).

originate in the same volume a single value of the temperature should be applied in their reduction, and if the relative abundance ratios were the same as in Orion the three curves in Figure 2 would intersect in a single point. From Figure 2 and Table 5 it can be seen that this is not the case. We expect the errors in the abundance ratios to be smaller than 0.30 in the logarithm, therefore the differences between R7a and R7b might not be significant; alternatively we consider significant the differences between the Orion and Barnard Loop nebulae.

As mentioned before, the abundance ratios derived for the Orion Nebula are similar to the solar ones, while those derived from the *Copernicus* data indicate a deficiency in the interstellar medium of some of the heavy elements. It is to be expected that a considerable fraction of the dust particles has been destroyed in the center of the Orion Nebula, the region from which the results by Peimbert and Costero (1969) were mainly derived. An argument in favor of this idea is that the dust to gas ratio in Orion, derived from observations of the scattered light (O'Dell and Hubbard 1965), is very small in comparison to the ratio in the general interstellar medium. On the other hand, the ultraviolet scattered light in the Barnard Loop Nebula is appreciable (O'Dell *et al.* 1967). Therefore it might be expected that the fraction of heavy elements embedded in dust grains in the Barnard Loop is typical of the low density interstellar medium and consequently that some of the heavy elements in the gas might be deficient in the Barnard Loop, relative to the Orion Nebula. Moreover, from the *Copernicus* observations (Morton *et al.* 1973), it is found that while nitrogen is in general normal in the interstellar clouds, oxygen is very often deficient. This is particularly the case in the direction of λ Ori, a star very close to the Barnard Loop. We think that it is reasonable to assume that the nitrogen abundance is similar in both nebulae and that oxygen therefore is underabundant by a factor of two to four in the Barnard Loop. It can be shown that density fluctuations do not affect this result. The presence of any type of inhomogeneity of the temperature along the line of sight would yield a larger underabundance of oxygen with respect to nitrogen.

The assumption of a normal nitrogen to hydrogen abundance ratio implies an electron temperature of ~6500°K for the Barnard Loop Nebula. This temperature is in good agreement with the upper limit of 8000°K for the low density interstellar medium determined by Reynolds *et al.* (1973) from the widths of emission lines in directions close to the galactic anticenter.

There is another consideration in favor of a normal nitrogen abundance provided by the nitrogen to sulphur abundance ratio. From Benvenuti *et al.* (1973) we have

$$\frac{N(N^+)}{N(S^+)} = 3.43 \exp(5.0 \times 10^2/T_e) \frac{I(6584)}{I(6717 + 6731)} \qquad (13)$$

for the assumption that the N^+ and S^+ lines originate in the same volume; using this expression and the observed values presented in Table 3 we obtain log N(N)/N(S) = +0.50. This value is somewhat higher than that derived for the Orion Nebula. However the sulphur abundance in the Orion Nebula was derived mainly from the forbidden lines of [S III] and different ionization considerations. The *Copernicus* observations also indicate that sulphur is in general normal; this is particularly the case for λ Ori. Therefore the nitrogen to sulphur ratio indicates a slight overabundance of nitrogen that can be due to the different procedure used to determine the sulphur abundance; in any case, the derived ratio is against the possibility of nitrogen being underabundant.

Our observations do not rule out the possibility that nitrogen is overabundant and oxygen is normal in the Barnard Loop Nebula. However the data from *Copernicus* do not give support to this alternative. To decide on this question an independent determination of the electron temperature is needed.

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