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CHEMICAL ABUNDANCES OF NGC 5461 AND NGC 5471 DERIVED FROM ECHELLE SPECTROPHOTOMETRY

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RESUMEN

Presentamos espectrofotometría de alta resolución de NGC 5461 y NGC 5471, dos regiones H II gigantes en la galaxia M101. Los datos se obtuvieron con el telescopio de 2.1 m del Observatorio Astronómico Nacional en San Pedro Mártir, Baja California. Medimos las intensidades de un conjunto de líneas de recombinación de hidrógeno y de helio, así como líneas prohibidas de un gran número de iones. Calculamos las condiciones físicas en las dos nebulosas y calculamos las abundancias químicas totales tomando en cuenta las abundancias iónicas observadas así como las no observadas; estas últimas las estimamos a partir de factores de corrección de ionización (*icf*'s). Para NGC 5461 los *icf*'s se basan en un modelo detallado de fotoionización diseñado específicamente para este objeto (Luridiana & Peimbert 2001), mientras que para NGC 5471 se obtuvieron a partir de un modelo de fotoionización para NGC 2363 (Luridiana, Peimbert, & Leitherer 1999), región que muestra un grado de ionización muy semejante al de NGC 5471. Los *icfs* así determinados los comparamos con aquellos que se obtienen a partir de las fórmulas de Mathis & Rosa (1991). Dicha comparación muestra importantes discrepancias para algunos de los elementos incluyendo nitrógeno, neón y cloro.

ABSTRACT

We present high resolution spectroscopic data of the two giant extragalactic H II regions NGC 5461 and NGC 5471 in M101, which have been obtained with the 2.1-m telescope of the Observatorio Astronómico Nacional in San Pedro Mártir, Baja California. We measured the intensities of several H and He recombination lines, and of forbidden lines of a large number of ions. We calculate the physical conditions in the two nebulae with a large number of diagnostics and determine their chemical abundances by applying ionization correction factors (*icf*'s) to the observed ionic abundances. For NGC 5461, the *icf*'s are based on a tailored photoionization model of the region (Luridiana & Peimbert 2001), while for NGC 5471 they are computed from those predicted by a photoionization model of NGC 2363 (Luridiana, Peimbert, & Leitherer 1999), a region which is similar to NGC 5471 in the ionization structure. For both regions, the *icf*'s are compared to those computed following the prescriptions by Mathis & Rosa (1991). Such comparison shows large discrepancies for several elements, including nitrogen, neon, and chlorine.

Key Words: **H II REGIONS — ISM: ABUNDANCES — ISM: INDIVIDUAL (NGC 5461, NGC 5471)**

1. INTRODUCTION

NGC 5461 and NGC 5471 are two giant extragalactic H II regions (GEHRs), located in the spiral galaxy M 101 (NGC 5457). Due to their prominence, the two GEHRs have been extensively studied by many authors. Low- and medium-resolution spectroscopic data in several wavelength intervals, ranging from the IR to the UV, of one or both regions have been published by Rayo, Peimbert, & Torres-Peimbert (1982), McCall, Rybski, & Shields (1985), Torres-Peimbert, Peimbert, & Fierro (1989), Skillman & Israel (1988), Castañeda, Vílchez, & Copetti

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TABLE 1

JOURNAL OF OBSERVATIONS

Date	Spectral Range	Orders	Designation	Slit Size	Exposure Times (seconds) NGC 5461	NGC 5471
96 Jun 10	6280–9100 Å	25–35	Near IR	$39.9 \times 4''$	60, 3×1200	60, 2×600, 1200
96 Jun 13	3450–6650 Å	34–64	Blue	$13.3 \times 4''$	180, 2×900	180, 2×600, 900

(1992), Rosa & Benvenuti (1994), and Garnett et al. (1999). Theoretical models covering different properties of the two regions have been described by Evans (1986), Castañeda et al. (1992), and Luridiana & Peimbert (2001). The chemical composition of the two regions has been determined by Torres-Peimbert et al. (1989), who aimed at determining the chemical gradients of the parent galaxy.

In the present paper, we present high-resolution spectroscopic data of both H II regions covering a wide spectral range, from near-ultraviolet to near-infrared. The use of the echelle cross disperser produces deep high-resolution spectra of a large number of lines in the whole optical domain, overcoming the problem of line-blending, and allowing the application of a large number of physical-condition diagnostics. The structure of the paper is as follows: in § 2 we describe the observations and the reduction procedure; in § 3 we present the line intensities of the two regions; in § 4 we derive the physical conditions in the two nebulae, and calculate their chemical abundances by means of standard techniques; and finally, in § 5 we discuss our results and their implications.

2. OBSERVATIONS AND DATA REDUCTION

The observations were carried out with the 2.1-m telescope of the Observatorio Astronómico Nacional in San Pedro Mártir, Baja California, México, in June 1996. The telescope was in its f/7.5 configuration. High resolution CCD spectra were obtained using the REOSC Echelle Spectrograph; see Levine & Chakrabarty (1994) for a description of the general characteristics of this instrument. The echelle gives a resolution of 0.234 Å pixel^{-1} at Hα using the University College of London (UCL) camera and a CCD-Tek chip of 1024×1024 pixels with a 24 μm^2 pixel size. The spectral resolution is 0.5 Å FWHM and the accuracy in the wavelength determination of emission lines is 0.1 Å.

For both regions, we obtained spectra in two partially overlapped wavelength intervals covering the range from 3450 to 9100 Å. Typically, three or four individual exposures were added to obtain the final spectra in each interval. Slits covering $13.3'' \times 4''$ in the blue and $39.9'' \times 4''$ in the near-infrared (NIR) were used to avoid overlapping between orders in the spatial direction. The slit orientation was east-west in all cases. A journal of the observations is presented in Table 1.

The atmospheric refraction depends on the observed wavelength; therefore the region of the sky included in the slit varies with wavelength. This problem is called the atmospheric differential refraction problem. The differences in pointing caused by the atmospheric differential refraction are not important because the objects and the slit are relatively large. According to the slit size, the slit orientation, the airmass ($1.09 < \sec z < 1.27$), and the tables by Filippenko (1982), the difference between the sampled region by Hβ and that sampled by any other line is at most 8%; this difference will barely affect the line intensities because the object is considerably wider than the slit.

We used a Th-Ar lamp for wavelength calibration in all spectral ranges and a tungsten bulb for internal flat-field images. The absolute flux calibration of all the spectra was achieved by taking echellograms of the standard stars HR 4963, HR 5501 and HR 7596. All of them are from the list of Hamuy et al. (1992), which includes bright stars with fluxes sampled at 16 Å steps. An average curve for atmospheric extinction was used (Schuster 1982).

The spectra were reduced using the IRAF[4] echelle reduction package, following the standard procedure of bias subtraction, aperture extraction, flatfielding, wavelength calibration and flux calibration.

3. THE EMISSION-LINE SPECTRA

The line fluxes and the dereddened intensities for NGC 5461 and NGC 5471, normalized to $I(\mathrm{H}\beta) = 100$, are listed in Table 2. The line fluxes were measured with the `splot` task of IRAF. The central

[4]IRAF is distributed by NOAO, which is operated by AURA, under cooperative agreement with NSF.

TABLE 2

OBSERVED AND REDDENING-CORRECTED LINE RATIOS

		NGC 5461			NGC 5471		
Ion	λ_0(Å)	λ_{obs}(Å)	$F(\lambda)^a$	$I(\lambda)^a$	λ_{obs}(Å)	$F(\lambda)^a$	$I(\lambda)^a$
[O II]	3726.03	3728.70	62.00	85.96	3729.01	38.53	43.91
[O II]	3728.82	3731.44	76.16	105.49	3731.75	51.21	58.34
H I	3835.00	3838.22	5.59	7.48	3838.66	5.57	6.26
[Ne III]	3868.75	3871.60	13.13	17.33	3872.11	44.33	49.54
He I	3888.65	3891.71	17.84	23.48	3892.20	20.81	23.22
H8	3889.05						
[Ne III]	3967.47	3970.54	3.62	4.62	3970.98	14.03	15.47
H7	3970.00	3973.15	13.62	17.37	3973.58	14.05	15.49
He I	4026.19	4029.50	1.68	2.12	4029.87	2.04	2.24
[S II]	4068.60	4071.74	1.25:	1.56:	4071.97	0.79:	0.86:
[S II]	4076.22	4079.30	0.53:	0.66:	4079.72	0.64:	0.70:
Hδ	4101.74	4105.03	23.59	29.09	4105.46	24.47	26.61
Hγ	4340.47	4344.11	47.53	54.67	4344.58	46.45	49.12
[O III]	4363.00	4366.76	1.04	1.19	4367.35	8.86	9.35
He I	4388.00	4391.63	0.33:	0.38:	···	···	···
He I	4471.48	4475.26	4.47	4.98	4475.76	3.96	4.13
He II	4685.68	···	···	···	4690.45	0.38	0.39
[Ar IV]	4711.34	···	···	···	4715.86	1.43	1.45
[Ar IV]	4740.20	···	···	···	4745.10	1.17	1.18
Hβ	4861.33	4865.54	100.00	100.00	4866.05	100.00	100.00
He I	4921.93	4925.97	1.50	1.48	4926.85	0.95	0.95
[O III]	4958.92	4963.28	114.52	112.17	4963.80	232.86	230.94
[O III]	5006.85	5011.15	333.51	323.98	5011.70	684.10	676.22
[Cl III]	5517.45	5522.52	0.54:	0.47:	5522.92	0.33:	0.31:
[N II]	5754.57	5759.55	0.48	0.40	5759.45	0.35:	0.32:
He I	5875.67	5880.65	16.62	13.37	5881.28	12.35	11.32
[O I]	6300.32	6306.11	5.57	4.13	6306.34	4.41	3.92
[S III]	6312.06	6317.36	1.76	1.29	6317.90	1.82	1.62
[O I]	6363.81	6369.17	0.97	0.71	6369.69	0.90	0.80
[N II]	6548.03	6553.59	21.02	14.90	···	···	···
Hα	6562.82	6567.83	408.31	288.57	6568.54	321.83	280.11
[N II]	6583.41	6588.93	59.33	41.71	6589.45	8.62	7.48
He I	6678.15	6684.01	4.80	3.31	6684.60	3.73	3.21
[S II]	6716.47	6722.27	29.42	20.07	6722.74	12.70	10.90
[S II]	6732.07	6736.64	22.90	15.59	6737.12	9.44	8.09
He I	7065.28	7070.84	3.22	2.13	7071.71	2.85	2.41
[Ar III]	7135.93	7141.91	15.52	10.12	7142.49	7.91	6.68
[O II]	7319.65	7326.60	3.49	2.22	7327.25	1.99	1.66
[O II]	7330.16	7337.01	3.03	1.93	7337.26	1.96	1.63
[S III]	9068.90	9076.42	53.34	28.47	9077.07	24.23	18.84
log F(Hβ)[b]			−12.41			−12.53	
log EW(Hβ)[c]			2.18			2.13	
C(Hβ)			0.45 ± 0.06			0.18 ± 0.06	

[a]Normalized to Hβ = 100.00. [b]Units of erg sec^{-1} cm^{-2}. [c]Units of Å.

wavelengths were measured with splot and referred to the heliocentric reference frame. The observational uncertainties associated with the line flux intensities are estimated to be 0.02 dex for those lines with $F(\lambda)/F(\mathrm{H}\beta) \geq 0.10$, 0.04 dex for those lines with $0.02 \leq F(\lambda)/F(H\beta) < 0.10$, and 0.08 dex for those lines with $F(\lambda)/F(\mathrm{H}\beta) < 0.02$. Those lines marked with a colon are affected by an uncertainty of about 0.15 dex.

Since the NIR and the blue spectra have been taken with different apertures, it is advisable to correct for this effect (as well as for possible shifts in the telescope position from one night to another) to compute line ratios in a homogeneous manner. For this reason, we applied a grey shift to the line intensities of the NIR spectra lines, by matching the Hα intensities. The intensity of the blue spectrum has been considered for those lines falling in both wavelength ranges ([O I] $\lambda\lambda$ 6300, 6363, [N II] $\lambda\lambda$ 6548, 6584, [S III] λ 6312, and Hα). The shift applied was +0.032 dex for NGC 5461 and −0.109 dex for NGC 5471. Note that for NGC 5461 $I(\mathrm{H}\alpha)_{\mathrm{blue}}/I(\mathrm{H}\alpha)_{\mathrm{NIR}} > 1$, even though the slit used in the blue range was smaller than the one used in the NIR: this fact probably implies that the telescope was not pointing exactly to the same position during the two nights, an effect amplified by the extremely-peaked brightness distribution of the region. Indeed, Figure 13 in Castañeda et al. (1992) and Figure 3 in Luridiana & Peimbert (2001) show that the Hα intensity falls to less than 10% of the peak value within $3''$ from the center.

The NIR lines were corrected for telluric absorption; this correction was smaller than 3% for all the lines with the exception of $\lambda\lambda$7320, 9069 in NGC 5461 where the correction amounted to 6% and 7%, and of λ9069 in NGC 5471 where the correction amounted to 9%. The reddening coefficient, $C(\mathrm{H}\beta)$, was determined comparing the $I(\mathrm{H}\beta)/I(\mathrm{H}\alpha)_{\mathrm{blue}}$ observed ratio to the case B one computed by Storey & Hummer (1995) adopting $T_{\mathrm{e}} = 8700$ K and $N_{\mathrm{e}} = 150$ cm^{-3} for NGC 5461, and $T_{\mathrm{e}} = 12,900$ K, $N_{\mathrm{e}} = 90$ cm^{-3} for NGC 5471. The uncertainty in $C(\mathrm{H}\beta)$ has been estimated assuming a 5% uncertainty in $I(\mathrm{H}\beta)$ and $I(\mathrm{H}\alpha)_{\mathrm{blue}}$. The results are shown in Table 2, together with the total uncorrected Hβ fluxes, measured in erg s^{-1} cm^{-2}, the equivalent widths of Hβ, and the reddening coefficients.

4. PHYSICAL CONDITIONS AND CHEMICAL ABUNDANCES

The physical conditions in the two nebulae have been calculated with the ntplot and the temden IRAF (version 2.11.3) tasks. These tasks are based on 5-level model atoms for [O II], [S III], [Cl III], and [Ar IV], 6-level model atoms for [O III] and [N II], and an 8-level model atom for [S II]. The ntplot task allows a self-consistent computation of N_{e} and T_{e} for a given ion, when the relevant line ratios are known; it was used to determine N_{e}(O II), T_{e}(O II), and N_{e}(S II), T_{e}(S II) for both H II regions. When only one line ratio is known for a given ion, the task temden is used, which computes T_{e} for an assumed N_{e} value or vice versa. T_{e}(N II), T_{e}(O III), and T_{e}(S III) were calculated with temden assuming $N_{\mathrm{e}} = N_{\mathrm{e}}$(O II), and N_{e}(Ar IV) was calculated assuming $T_{\mathrm{e}} = T_{\mathrm{e}}$(O III). It is worthwhile to remark that the high resolution and wide wavelength range of these observations considerably extends the number of available physical-condition diagnostics of the two H II regions, adding N_{e}(O II), N_{e}(Ar IV) and T_{e}(S III) to the diagnostics studied in previous works.

Table 3 lists the physical conditions of the two nebulae. The results obtained are in good agreement with those by Torres-Peimbert et al. (1989) within the estimated errors. The only notable exception is T_{e}(S II), for which Torres-Peimbert et al. (1989) found much higher values in both objects. However, such differences depend on the atomic parameters used, rather than on differences in the measured line ratios: indeed, using the intensity values of Torres-Peimbert et al. (1989) and the same atomic parameters as us, one would obtain slightly lower temperatures than ours (the atomic parameters used in this paper are those from Verner, Verner, & Ferland 1996, Keenan et al. 1993, and Ramsbottom, Bell, & Stafford 1996).

The root mean square density, N_{e}(rms), to a very good approximation is given by the expression:

$$N_{\mathrm{e}}(\mathrm{rms}) = \left\{ \frac{I(\mathrm{H}\beta)\,[1 + N(\mathrm{He}^{+})/N(\mathrm{H}^{+})]\,4\pi d^{2}}{V\,\alpha(\mathrm{H}\beta, T_{\mathrm{e}})\,h\nu_{\mathrm{H}\beta}} \right\}^{1/2}, \tag{1}$$

where V is the observed volume, $\alpha(\mathrm{H}\beta, T_{\mathrm{e}})$ is the Hβ effective recombination coefficient, and d is the distance to the region. We assume $V = 4\pi r^{3}/3$, where r is the radius of a circle equivalent in area to our slit, at a distance of 7.4 Mpc (Sandage & Tammann 1976, with the suggested correction by de Vaucouleurs 1978). The results, substantially equivalent to those of Torres-Peimbert et al. (1989), are also listed in Table 3. From these values, combined with N_{e}(O II) or N_{e}(S II), we can calculate the filling factor, which is $0.009 \lesssim \epsilon \lesssim 0.011$ for NGC 5461 and $0.013 \lesssim \epsilon \lesssim 0.022$ for NGC 5471. These values can be compared to the filling factor of the com-

TABLE 3

ELECTRON TEMPERATURES AND DENSITIES OF NGC 5461 AND NGC 5471

Quantity[a]	NGC 5461		NGC 5471	
T_e(O II)	$10{,}400 \pm 500$	9500 ± 900	$14{,}200 \pm 900$	$13{,}100 \pm 2000$
T_e(S II)	8000 ± 1600	9500 ± 1100	$10{,}000 \pm 3200$	$12{,}700 \pm 2400$
T_e(N II)	8700 ± 700	8500 ± 550	$10{,}800 \pm 2300$	$10{,}800 \pm 1700$
T_e(O III)	8500 ± 500	9300 ± 250	$13{,}000 \pm 500$	$13{,}400 \pm 250$
T_e(S III)	9000 ± 800	...	$12{,}100 \pm 800$	...
N_e(O II)	150 ± 60	...	90 ± 70	...
N_e(S II)	130 ± 90	234	$70 \pm ^{100}_{70}$	186
N_e(Ar IV)	...	...	$1350 \pm ^{1150}_{920}$	...
N_e(rms)	14.2	14.8	10.4	10.6
References	1	2	1	2

[a]Given in K and cm^{-3}, respectively. REFERENCES:— (1) This work; (2) Torres-Peimbert et al. 1989.

posite model of NGC 5461 by Luridiana & Peimbert (2001), which averages 0.003. The lower filling factor derived by Luridiana & Peimbert (2001) was based on the data by Torres-Peimbert et al. (1989), which obtained a higher N_e(S II) than that derived here.

Small filling factors of ~ 0.01 are characteristic of GEHRs (Shields 1986). Similar values of about 0.02 have been found in the ionized gas of emission-line dwarf galaxies (Martin 1997). In contrast, Copetti et al. (2000) find a mean filling factor of 0.1 for a sample of 15 Galactic "normal" H II regions. Although the estimations of ϵ in ionized nebulae are indirect and very rough, the difference between "normal" and giant H II regions—if real—would imply a higher clumpiness in the giant ones. This is not unexpected considering the typical highly disturbed morphology and complex kinematics of GEHRs, that may be produced by the dynamical effects of stellar winds and supernovae in GEHRs.

4.1. *Ionic Abundances*

4.1.1. *Heavy Elements*

The ionic abundances of heavy elements in the two regions have been calculated with the IRAF task `abund`, which is based on a three-zone model of the nebula, with the three zones corresponding to the low-, medium-, and high-ionization regions, each characterized by representative N_e and T_e values.

Concerning the temperature, each of the three low-ionization diagnostics available—T_e(N II), T_e(S II), and T_e(O II)—is affected by uncertainties: (a) Nitrogen lines are weak in these objects, especially in NGC 5471. (b) T_e(O II) depends non-negligibly on the assumed reddening, and on the assumed density; furthermore, [O II] $\lambda\lambda$ 7320, 7330 are weak and affected by telluric absorption lines. Finally, (c) [S II] $\lambda\lambda$ 4068, 4076 are also weak, and the estimates of the [S II] atomic parameters are constantly changing; additionally, T_e(S II) has a dependence on the assumed N_e similar to that of T_e(O II). To minimize these uncertainties, we decided to adopt the average temperature of the three diagnostics, i.e., $T_e = 9000$ K for NGC 5461 and $T_e = 11,700$ K for NGC 5471. Finally, in both the medium- and high-ionization zones we adopted T_e(O III) as a representative temperature in both regions, since T_e(S III) is more uncertain due to the observational errors in the sulfur lines and the frequent revisions of the [S III] atomic parameters.

Concerning the electronic density, we adopted in the three zones of both H II regions $N_e = N_e$(O II). We preferred N_e(O II) over N_e(S II), due to the following facts: (a) the [O II] lines are more intense than the [S II] lines, (b) the [O II] electronic density diagnostic is slightly more sensitive than the [S II] one in the low-density regime, and (c) the [S II] atomic parameters are still highly uncertain.

With these assumptions, we have obtained the abundances of N^+, O^0, O^+, O^{++}, Ne^{++}, S^+, S^{++}, Cl^{++}, Ar^{++}, and Ar^{3+} (Table 4).

4.1.2. *Helium*

There are 8 lines of the He I recombination spectrum observed in NGC 5461 and 7 lines in NGC 5471. To calculate the He^+ abundance, it is necessary to correct the line intensities for the two well-known effects of self-absorption and collisional enhancement. The correction for self-absorption

TABLE 4

IONIC ABUNDANCES[a] IN NGC 5461 AND NGC 5471

Ion	NGC 5461	NGC 5471
O^0	7.08 ± 0.20	6.63 ± 0.20
O^+	8.08 ± 0.14	7.32 ± 0.14
O^{++}	8.32 ± 0.07	8.02 ± 0.07
N^+	7.04 ± 0.12	6.01 ± 0.13
Ne^{++}	7.59 ± 0.11	7.32 ± 0.10
S^+	6.02 ± 0.19	5.47 ± 0.20
S^{++}	7.00 ± 0.10	6.45 ± 0.10
Cl^{++}	4.93 ± 0.16	4.20 ± 0.16
Ar^{++}	6.15 ± 0.12	5.55 ± 0.14
Ar^{3+}	...	5.07 ± 0.10

[a]Given as $12 + \log(X^{+i}/H^+)$.

may be rather uncertain for λ 3889 and λ 7065; furthermore the observational errors in the line intensities of $\lambda\lambda$ 4026, 4388, and 4922 are relatively large. Consequently we decided to determine the He^+ abundances based on the $\lambda\lambda$ 4471, 5876 and 6678 lines.

The He^+ abundance can be computed for each He I line by means of the relation:

$$y^+ \equiv \frac{He^+}{H^+} = \frac{\lambda}{4861} \frac{\alpha_{\rm eff}(H\beta)}{\alpha_{\rm eff}(\lambda)} \frac{I(\lambda)^{\rm R}}{I(H\beta)}, \qquad (2)$$

where $\alpha_{\rm eff}(\lambda)$ is the effective recombination coefficient of the considered transition, and $I(\lambda)^{\rm R}$ is the observed intensity of the considered line, corrected for collisional enhancement and optical depth effects.

The collisional contribution to the helium lines was estimated from Kingdon & Ferland (1995) and Banjamin, Skillman, & Smits (1999) assuming $T_{\rm e} =$ 8700 K and $N_{\rm e} = 150$ cm^{-3} for NGC 5461, and $T_{\rm e} = 12,900$ K and $N_{\rm e} = 90$ cm^{-3} for NGC 5471. We decided to adopt for the temperature a weighted average of T(O III) as representative of the O^{++} region and an average of T(O II), T(S II) and T(N II) as representative of the O^+ region; since the emissivity is dominated by the O^{++} region the adopted temperatures are closer to the T(O III) values. The self absorption effects in the triplet lines were estimated from the computations by Robbins (1968), adopting $\tau(3889) = 1.0$ and 0.2 for NGC 5461 and NGC 5471, respectively. The $\tau(3889)$ values were estimated from the $\lambda\lambda$ 3889 and 7065 line intensities and from the photoionization model of NGC 5461 by Luridiana & Peimbert (2001) computed with CLOUDY (Ferland 1996). The $\alpha_{\rm eff}(\lambda)$ coefficients at $T_{\rm e} = 8700$ K (NGC 5461) and $T_{\rm e} = 12,900$ K (NGC 5471) have been obtained by power-law interpolation in the appropriate temperature interval between the data provided by Smits (1996) for $N_{\rm e} = 100$ cm^{-3}. Given the low densities of the two H II regions, the correction for collisional enhancement is generally small; similarly, the correction for optical depth effects is very small because $\tau(3889)$ is relatively small. Finally, the effective recombination coefficient for Hβ is based on the data by Brocklehurst (1971) for $N_{\rm e} = 100$ cm^{-3}, assuming a power-law interpolation for $T_{\rm e} = 8700$ K (NGC 5461) and $T_{\rm e} = 12,900$ K (NGC 5471).

TABLE 5

HELIUM ABUNDANCE VALUES

	y^+	
Line	NGC 5461	NGC 5471
4471	0.0983	0.0846
5876	0.0945	0.0867
6678	0.0836	0.0879
Mean value	0.0937	0.0864

Table 5 presents the resulting y^+ values, together with the mean value. The mean value was obtained by weighting the different lines as the square root of their intensities.

There are three minor effects that were not considered in the helium abundance determination: (a) the correction due to the temperature structure, (b) the correction due to the collisional excitation of the Balmer lines and (c) the correction for the underlying absorption of the helium lines. To estimate the first two effects observations of higher accuracy are required (e.g., Peimbert, Peimbert, & Ruiz 2000; Peimbert, Peimbert, & Luridiana 2002; Luridiana, Peimbert, & Peimbert 2002), the third effect is considered by Esteban et al. (2002) for these objects.

In NGC 5471, He II λ 4686 is also observed, implying the presence of He^{++}. The abundance of He^{++} relative to H^+ can be computed by means of the equation:

$$\frac{He^{++}}{H^+} = \frac{4686}{4861} \frac{\alpha_{\rm eff}(H\beta)}{\alpha_{\rm eff}(4686)} \frac{I(4686)}{I(H\beta)}, \qquad (3)$$

where the $\alpha_{\rm eff}(\lambda)$ coefficients at $T_{\rm e} = 12900$ K have been obtained by a power-law interpolation in temperature from the data provided by Smits (1996) for $N_{\rm e} = 100$ cm^{-3}. The result of this calculation is $He^{++}/H^+ = 3.9 \times 10^{-4}$, a completely negligible quantity from the point of view of the total abundance. It is interesting to note that in our spectra the nebular He II λ 4686 line is superposed on a much broader stellar line, about 3.5 times more intense than the nebular line; the sum of the two components is roughly a factor of 1.7 higher than the $I(\lambda4686)$ reported by Torres-Peimbert et al. (1989), while the nebular line alone is about one third of it. These differences are probably a combination of aperture effects, and the much lower resolution used by Torres-Peimbert et al. (1989).

The broad component of λ 4686 is due to WR stars; in addition we also observe stellar features of N V 4602, 4620, C IV 4658, and C IV 5808, whereas N III 4640 and C III 4650 are not detected (see Table 6). All the detected lines carry uncertainties of the order of 20%. The N V 4602, 4620 feature implies the presence of WN stars, while the two C IV features implies the presence of WC or WO stars; the low 4658/5808 intensity reatio, compared to the observed ratios compiled by Schaerer & Vacca (1998), might suggest that the WO stars dominate and the WC stars are not numerous or even absent. However, it is not possible to interpret quantitatively the observed WR features in terms of a distribution among the various WR spectral types, due to the uncertainties both in our observations and in the calibration of WR spectra. Nevertheless, we can give a rough estimate of the *total* number of WR stars, using average values for the "WR bump" luminosities for WN and WC stars (Smith 1991; Schaerer & Vacca 1998): We obtain in this way 14 "equivalent" WC4 stars and 26 "equivalent" WN7 stars; the WC4 stars account for all the 5808 Å bump flux, and almost one half of the N III/V + C III/IV + He II blend around 4650 Å, and the WN7 stars for the rest of the flux in the N III/V + C III/IV + He II blend. On the other hand, the observed Hβ flux corresponds to a number of ionizing photons $Q(\mathrm{H}^0) \sim 5 \times 10^{51}$ s^{-1} (assuming 0.8 for the covering factor), or 450 equivalent O7V stars (Vacca 1994) ; for a Salpeter's IMF with $M_{\mathrm{up}} = 120\ M_\odot$, this corresponds to a total number of about 530 O stars in the region (Schaerer & Vacca 1998). From these estimates we derive a WR/O ratio of $40/530 \sim 0.075$.

4.2. *Chemical Abundances*

The chemical abundances for both H II regions were calculated under the assumption of no temperature fluctuations, and without considering the fraction of heavy elements trapped in dust. The resulting values are listed in Table 7, which also contains the gaseous abundances derived by Torres-Peimbert et al. (1989) under the assumption that $t^2 = 0$, and the Orion and solar chemical abundances compiled from the literature. For both objects the Y values derived by us are higher than those derived by Torres-Peimbert et al. (1989): we prefer our values due to the higher resolution of our spectra. For NGC 5461 the N/O and Ne/O values derived by us are higher than those of Torres-Peimbert et al. (1989): the difference is mostly due to differences in the *icf*'s used by the two groups. For NGC 5471 the N/O and Ne/O values derived by us are similar to those by Torres-Peimbert et al. (1989), but in this case the *icf*'s used were almost the same. The gaseous values for the heavy species in Orion are taken from Esteban et al. (1998), with the exception of argon that was taken from Peimbert (1993); the solar values are taken from Holweger (2001) (N and Ne), Grevesse & Sauval (1998) (S, Cl, and Ar), and from Christensen-Dalsgaard (1998) (He), while the oxygen abundance is an average of the values cited in Allende-Prieto, Lambert, & Asplund (2001) and Holweger (2001).

TABLE 6

STELLAR LINES OF NGC 5471

λ (Å)	Ion	$F(\lambda)$[a]	$I(\lambda)$[a]	$L(\lambda)$[b]
4604 + 4620	N V	5.6	9.0	5.9
4658	C IV	4.9	7.8	5.1
4686	He II	3.9	6.3	4.1
5801 + 5812	C IV	4.5	6.5	4.3

[a]Units: 10^{-15} erg cm^{-2} s^{-1}. [b]Units: 10^{+37} erg s^{-1}.

4.2.1. *NGC 5461*

The computation of the chemical abundances from the observed ionic abundances requires a knowledge of the ionization structure of the model. In the case of NGC 5461, we can rely on the ionization structure predicted by the photoionization model of Luridiana & Peimbert (2001 and private communication). Radial and volumetric integrations of the ionic fractions are presented in Table 8. The radial average for a given ion X^i is defined as

$$\left(\frac{\mathrm{X}^i}{\mathrm{X}}\right)_R \equiv \int_0^{R_\mathrm{S}} N(\mathrm{X}^i)\, N_\mathrm{e}\, dR \Bigg/ \int_0^{R_\mathrm{S}} N(\mathrm{X})\, N_\mathrm{e}\, dR, \quad (4)$$

while the volume average is:

$$\left(\frac{\mathrm{X}^i}{\mathrm{X}}\right)_V \equiv \int_V N(\mathrm{X}^i)\, N_\mathrm{e}\, dV \Bigg/ \int_V N(\mathrm{X})\, N_\mathrm{e}\, dV. \quad (5)$$

From these average ionic ratios, the ionization correction factors can be easily computed, e.g., for

TABLE 7

GASEOUS CHEMICAL ABUNDANCES IN NGC 5461, NGC 5471, ORION, AND THE SUN

Element	NGC 5461 ($t^2 = 0$)		NGC 5471 ($t^2 = 0$)		Orion ($t^2 = 0.024$)	Sun
Y	0.285 ± 0.011	0.264 ± 0.007	0.257 ± 0.010	0.241 ± 0.007	0.276 ± 0.007	0.271 ± 0.010
$12 + \log$ O/H	8.52 ± 0.10	8.39 ± 0.08	8.10 ± 0.08	8.05 ± 0.05	8.64 ± 0.06	8.71 ± 0.05
log N/O	-0.64 ± 0.12	-1.13 ± 0.06	-1.23 ± 0.10	-1.33 ± 0.06	-0.85 ± 0.10	-0.78 ± 0.12
log Ne/O	-0.44 ± 0.12	-0.68 ± 0.06	-0.73 ± 0.10	-0.63 ± 0.06	-0.74 ± 0.12	-0.71 ± 0.09
log S/O	-1.46 ± 0.11	-1.69 ± 0.08	-1.57 ± 0.10	-1.67 ± 0.08	-1.46 ± 0.12	-1.38 ± 0.12
log Cl/O	-3.54 ± 0.20	...	-3.67 ± 0.20	-3.30 ± 0.16	-3.21 ± 0.03	-3.21 ± 0.30
log Ar/O	-2.35 ± 0.12	-2.21 ± 0.08	-2.38 ± 0.15	-2.25 ± 0.08	-2.15 ± 0.21	-2.31 ± 0.08
References	1	2	1	2	3, 4	5, 6, 7, 8

References:— (1) This work; (2) Torres-Peimbert et al. 1989; (3) Esteban et al. 1998; (4) Peimbert 1993; (5) Allende-Prieto et al. 2001; (6) Holweger 2001; (7) Christensen-Dalsgaard 1998; (8) Grevesse & Sauval 1998.

the radial *icf*'s:

$$icf(\mathrm{X}^i)^{\mathrm{LP01},R} \equiv \frac{(\mathrm{X}/\mathrm{X}^i)}{(\mathrm{H}/\mathrm{H}^+)} = \frac{(\mathrm{H}^+/\mathrm{H})_R}{(\mathrm{X}^i/\mathrm{X})_R}, \quad (6)$$

and analogously for the volume-weighted ionization correction factors.

Helium. In NGC 5461 a non-negligible fraction of the total helium is in neutral form. According to the Luridiana & Peimbert (2001) model, such fraction is bracketed by the radial and the volume averages:

$$0.02 < \frac{\mathrm{He}^0}{\mathrm{He}} < 0.27. \quad (7)$$

To estimate the $\mathrm{He}^0/\mathrm{He}$ amount we will take a weighted average of the radial and volume average ionization structure presented in Table 7. The relative weights are 0.84 for the radial value and 0.16 for the volume average, and were obtained by adjusting the observed $\mathrm{S}^+/\mathrm{S}^{++}$ ratio to the ratio predicted by the model; this provides a good approximation since the ionization potential of He I is roughly equal to that of S II. From these relative weights we obtain that $\mathrm{He}^+/\mathrm{He} = 0.929$, and combining this value with the mean value of y^+ (see Table 5) we find:

$$\frac{\mathrm{He}}{\mathrm{H}} = y^+/0.929 = 0.1009, \quad (8)$$

or

$$Y = \frac{4 \times \mathrm{He/H}}{1 + 4 \times \mathrm{He/H} + 2 \times 16 \times \mathrm{O/H}} = 0.285, \quad (9)$$

where the assumption has been made that oxygen represents one half of all the mass in heavy elements, and 0.08 dex were added to the gaseous value for O/H derived below to take into account the fraction of oxygen trapped in dust grains.

Oxygen. The oxygen abundance was calculated by adding the observed ratios $N(\mathrm{O}^+)/N(\mathrm{H}^+)$ and $N(\mathrm{O}^{++})/N(\mathrm{H}^+)$:

$$\frac{\mathrm{O}}{\mathrm{H}} = \frac{\mathrm{O}^+ + \mathrm{O}^{++}}{\mathrm{H}^+}, \quad (10)$$

O^0 is not included in the sum since it is expected that the fraction of neutral oxygen is very similar to that of neutral hydrogen due to the charge-exchange reaction $\mathrm{O}^+ + \mathrm{H}^0 \rightarrow \mathrm{O}^0 + \mathrm{H}^+$ (see Osterbrock 1989, and Table 8 of this paper).

For the case of O^+ and O^{++}, the ionic ratios amount to 0.354 and 0.644 (radial averages), or 0.708 and 0.267 (volume averages), while the corresponding observed values are $\mathrm{O}^+/\mathrm{O}^{\mathrm{tot}}|_{\mathrm{obs}} = 0.352$ and $\mathrm{O}^{++}/\mathrm{O}^{\mathrm{tot}}|_{\mathrm{obs}} = 0.612$. The fact that the observed values are in much better agreement with the radial than with the volume averages, reflects the fact that the slits used for the observations sample only a small part of the region. For this reason, we will consider in the following only the radius-weighted ionization correction factors, and we will drop for simplicity the superscript R, i.e., $icf(\mathrm{X}^i)^{\mathrm{LP01}} \equiv icf(\mathrm{X}^i)^{\mathrm{LP01},R}$.

The neutral oxygen is underpredicted by the model, no matter which kind of average is considered (but particularly in the case of the radial average). This fact is a common finding in photoionization modeling (see, e.g., Stasińska & Schaerer 1999; Luridiana & Peimbert 2001), but from the point of view of the computation of the ionization correction factors, it has no consequences since the O^0 fraction is practically equal to the H^0 fraction.

Nitrogen. Only two nitrogen ionic species, N^+ and N^{++}, are expected in this H II region, and only N^+ is observed. The model of NGC 5461 gives for

TABLE 8

IONIZATION FRACTIONS FROM THE PHOTOIONIZATION MODEL OF NGC 5461[a]

	Ionization Stage							
	Log (Radial Average)				Log (Volume Average)			
Element	I	II	III	IV	I	II	III	IV
Hydrogen	−2.738	−0.001	···	···	−1.610	−0.011	···	···
Helium	−1.661	−0.009	···	···	−0.567	−0.137	···	···
Nitrogen	−3.045	−0.836	−0.069	−3.605	−1.785	−0.270	−0.351	−4.288
Oxygen	−2.822	−0.452	−0.191	···	−1.584	−0.150	−0.574	···
Neon	−2.842	−0.169	−0.494	···	−1.815	−0.058	−0.960	···
Sulfur	−5.322	−1.276	−0.042	−1.420	−4.247	−0.597	−0.132	−2.069
Chlorine	−4.716	−1.093	−0.041	−2.037	−3.644	−0.477	−0.177	−2.689
Argon	−3.585	−1.382	−0.023	−1.996	−2.283	−0.490	−0.175	−2.657

[a]Luridiana & Peimbert 2001.

the ionization correction factor of N^+:

$$icf(N^+)^{LP01} = 6.85, \tag{11}$$

where the radial average has been considered (see the previous section). It is interesting to compare this value with the one obtained for a "hot" region according to the method developed by Mathis & Rosa (1991):

$$icf(N^+)^{MR91} = 3.31. \tag{12}$$

yielding for the total nitrogen abundance a value 0.32 dex smaller than the one computed relying on the ionization structure of the model by Luridiana & Peimbert (2001). This difference is probably related—at least partially—to the consideration of the radius-averaged *icf*, which is less precise in the case of elements measured by means of lines observed with the longer slit. This hypothesis seems confirmed when one considers that the Mathis & Rosa (1991) result is bracketed by the radial and volume-averaged *icf*'s.

Neon. The Luridiana & Peimbert (2001) model of NGC 5461 gives:

$$icf(Ne^{++})^{LP01} = 3.12. \tag{13}$$

This value can be compared with the one predicted by the method of Mathis & Rosa (1991):

$$icf(Ne^{++})^{MR91} = 1.64, \tag{14}$$

which gives again a total neon abundance about a factor of 2 smaller than the one based on the Luridiana & Peimbert (2001) model. In this case, the difference cannot be explained in geometrical terms, as in the case of nitrogen and sulfur, since the volume-averaged $icf(Ne^{++})$ of the model by Luridiana & Peimbert, which amounts to 9.12, even further away from the Mathis & Rosa (1991) value. This difference should be studied further.

Sulfur. In the case of sulfur, a correction must be applied to the ionic abundances of S^+ and S^{++} to account for the presence of a small fraction of S^{3+} inside the H^+ sphere. The Luridiana & Peimbert (2001) model gives:

$$icf(S^+ + S^{++})^{LP01} = 1.04, \tag{15}$$

yielding the total sulfur abundance listed in Table 7. This *icf* is almost equal to 1, implying that the S/H ratio is robust. In what follows, we explore the additional information for the ionization structure provided by the S^+/S ratio.

The method by Mathis & Rosa (1991) gives:

$$icf(S^+)^{MR91} = 12.52, \tag{16}$$

while the photoionization model by Luridiana & Peimbert (2001) predicts

$$icf(S^+)^{LP01} = 18.88. \tag{17}$$

If the sulfur abundance were calculated from the observed S^+ ratio only, applying the method by Mathis & Rosa (1991), the value $\log S/O = -1.40$ would be obtained. This value is 0.07 dex higher than the value derived before, obtained by direct observations of both S^+ and S^{++}, combined with the $icf(S^+ + S^{++})$ by Luridiana & Peimbert (2001). On the other hand, the value obtained by correcting the observed S^+/H^+ by means of the *icf*(S^+) of Luridiana & Peimbert (2001) would be $\log S/O = -1.22$, a value 0.18 dex higher than the one in Table 7. An equivalent way of looking at the same discrepancy is to consider the S^+/S^{++} value, which is 0.100 according to observations, and 0.053 according to the Luridiana & Peimbert (2001) model. This discrepancy can be qualitatively explained when one considers that the S^+ abundance value is based on observations made with a larger slit than the one used in the case of, e.g., [O II] $\lambda\,3727$ and [O III] $\lambda\,5007$ (see Luridiana & Peimbert 2001): the radial average is thus a better approximation in the oxygen than in the sulfur case. This view is supported by considering that the observed S^+/S^{++} ratio is bracketed by the radial average ($S^+/S^{++}|_R = 0.053$) and the volume average ($S^+/S^{++}|_V = 0.253$). However, as we have seen before, the *icf*'s predicted by CLOUDY are in general discrepant from those predicted by Mathis & Rosa (1991), so that also in this case further investigation is needed to assess the origin of the discrepancy.

Chlorine. We adopted the *icf* of the model by Luridiana & Peimbert (2001) to determine the total chlorine abundance, which is:

$$icf(\mathrm{Cl}^{++})^{\mathrm{LP01}} = 1.10, \quad (18)$$

yielding a total chlorine abundance $\log \mathrm{Cl/O} = -3.54$. On the other hand, the value predicted by the method of Mathis & Rosa (1991) is:

$$icf(\mathrm{Cl}^{++})^{\mathrm{MR91}} = 2.22, \quad (19)$$

which yields $\log \mathrm{Cl/O} = -3.24$, a value very close to the solar one (see Table 7).

Argon. According to the Luridiana & Peimbert (2001) model, Ar^{++} accounts for 95% of the total argon, giving $icf(\mathrm{Ar}^{++})^{\mathrm{LP01}} = 1.05$ and implying the total abundance listed in Table 7, whereas the method by Mathis & Rosa (1991) gives $icf(\mathrm{Ar}^{++})^{\mathrm{MR91}} = 1.87$, which would imply for the total argon abundance a value 0.25 dex higher than the adopted value.

4.3. *NGC 5471*

For NGC 5471 we do not have a detailed photoionization model available, thus we shall rely on a photoionization model of NGC 2363.[5] NGC 2363 is a low-metallicity, high-excitation giant H II region, with a degree of ionization for the oxygen similar to that of NGC 5471. The model assumes $Z = 0.20\ Z_{\odot}$ and a $t = 3.0$ Myr instantaneous burst, which ionizes a spherical region, made up of two concentric shells of different densities; see Luridiana et al. (1999) for further details. To improve the approximation, we did not directly use the *icf*'s obtained from this model, but rather rescaled them to the actual observed ionic ratios. This procedure, which will be described more explicitly in the following sections, allows us to overcome possible differences related to the temperature and ionization structure of the two H II regions. The chemical abundances inferred for NGC 5471 are listed in Table 7, and will be discussed in detail in the following.

[5] More precisely, the model used is one of a series of simple burst models which constitute the extended-burst, composite model for NGC 2363.

Helium. The amount of neutral helium is probably negligible inside NGC 5471, as implied by its high ionization degree (its ionization degree is similar to that of M17 where it is found that the amount of neutral helium is negligible, see Peimbert, Torres-Peimbert, & Ruiz 1992; Esteban et al. 1999). Therefore, we find for the total helium abundance (see Table 5),

$$\frac{\mathrm{He}}{\mathrm{H}} = \frac{\mathrm{He}^{+} + \mathrm{He}^{++}}{\mathrm{H}^{+}} = 0.0868, \quad (20)$$

or

$$Y = \frac{4 \times \mathrm{He/H}}{1 + 4 \times \mathrm{He/H} + 2 \times 16 \times \mathrm{O/H}} = 0.257 \quad (21)$$

where the assumption has been made that oxygen represents one half of all the mass in heavy elements, and 0.08 dex were added to the gaseous value for O/H derived below to take into account the fraction of oxygen trapped in dust grains.

Oxygen. The oxygen abundance was calculated, as in the case of NGC 5461, by simply adding the observed ratios O^+/H^+ and O^{++}/H^+, so no assumptions on the ionization structure are necessary.

Nitrogen. We determined the nitrogen abundance using the observed N^+/O^+ ratio and the O^+/O, N^+/N ratios predicted by the model by Luridiana et al. (1999):

$$\frac{\mathrm{N}}{\mathrm{O}} = \left(\frac{\mathrm{N}^+}{\mathrm{O}^+}\right)_{\mathrm{obs}} \times \left(\frac{\mathrm{O}^+}{\mathrm{O}}\ \frac{\mathrm{N}}{\mathrm{N}^+}\right)_{\mathrm{LPL99}}. \quad (22)$$

Basically, this relation takes advantage of the similarity in the ionization structure of the two regions, rescaling to the observed O^+/O for a better approximation.

This equation yields for the total nitrogen abundance relative to oxygen the value $\log \mathrm{N/O} =$

−1.23 dex. It is interesting to compare this value to the one obtained by means of the Mathis & Rosa (1991) method. The criterion of Mathis & Rosa places NGC 5471 into the category of "hot" H II regions, so that:

$$icf(\mathrm{N}^+)^{\mathrm{MR91}} = 5.67, \tag{23}$$

which, combined with the observed value of N^+ gives $\log \mathrm{N/O} = -1.34$. On the other hand, with the usual assumption $\mathrm{N}^+/\mathrm{O}^+ = \mathrm{N/O}$ one would obtain $\log \mathrm{N/O} = -1.31$ dex. The difference between these two values and the one adopted by us is probably related to the non-negligible fraction of N^{+3} in the nebula, which is implicitly neglected by the empirical equation.

Neon. In the case of Ne^{++}, the scaling equation is:

$$\frac{\mathrm{Ne}}{\mathrm{O}} = \left(\frac{\mathrm{Ne}^{++}}{\mathrm{O}^{++}}\right)_{\mathrm{obs}} \times \left(\frac{\mathrm{O}^{++}}{\mathrm{O}}\,\frac{\mathrm{Ne}}{\mathrm{Ne}^{++}}\right)_{\mathrm{LPL99}}, \tag{24}$$

since the Ne^{++} coexists with O^{++}. We obtain for the total neon abundance $\log \mathrm{Ne/O} = -0.73$ dex. This result is intermediate between the prediction of the Mathis & Rosa (1991) method, giving:

$$icf(\mathrm{Ne}^{++})^{\mathrm{MR91}} = 1.05, \tag{25}$$

and $\log \mathrm{Ne/O} = -0.76$, and the usual empirical relation $\mathrm{Ne/O} = \mathrm{Ne}^{++}/\mathrm{O}^{++}$, yielding $\log \mathrm{Ne/O} = -0.70$.

Sulfur. The total sulfur abundance can be obtained from the following relations:

$$\frac{\mathrm{S}}{\mathrm{O}} \approx \left(\frac{\mathrm{S}^{++}}{\mathrm{O}^{+}}\right)_{\mathrm{obs}} \times \left(\frac{\mathrm{O}^{+}}{\mathrm{O}}\,\frac{\mathrm{S}}{\mathrm{S}^{++}}\right)_{\mathrm{LPL99}}, \tag{26}$$

and

$$\frac{\mathrm{S}}{\mathrm{O}} \approx \left(\frac{\mathrm{S}^{++}}{\mathrm{O}^{++}}\right)_{\mathrm{obs}} \times \left(\frac{\mathrm{O}^{++}}{\mathrm{O}}\,\frac{\mathrm{S}}{\mathrm{S}^{++}}\right)_{\mathrm{LPL99}}, \tag{27}$$

since S^{++} coexists with O^+ and O^{++}. We adopted the value which is obtained by the weighted average of equations (26) and (27), where the weight is determined by the observed O ionization fraction, and obtained $\log \mathrm{S/O} = -1.43$.

The Mathis & Rosa (1991) method gives:

$$icf(\mathrm{S}^+)^{\mathrm{MR91}} = 17.68, \tag{28}$$

implying $\log \mathrm{S/O} = -1.38$, in good agreement with the value derived with our model.

Chlorine. We determined the chlorine abundance with relations analogous to the ones used for sulfur:

$$\frac{\mathrm{Cl}}{\mathrm{O}} \approx \left(\frac{\mathrm{Cl}^{++}}{\mathrm{O}^{+}}\right)_{\mathrm{obs}} \times \left(\frac{\mathrm{O}^{+}}{\mathrm{O}}\,\frac{\mathrm{Cl}}{\mathrm{Cl}^{++}}\right)_{\mathrm{LPL99}} \tag{29}$$

and

$$\frac{\mathrm{Cl}}{\mathrm{O}} \approx \left(\frac{\mathrm{Cl}^{++}}{\mathrm{O}^{++}}\right)_{\mathrm{obs}} \times \left(\frac{\mathrm{O}^{++}}{\mathrm{O}}\,\frac{\mathrm{Cl}}{\mathrm{Cl}^{++}}\right)_{\mathrm{LPL99}}, \tag{30}$$

and using the same weighting procedure used for sulfur obtained $\log \mathrm{Cl/O} = -3.71$. The Mathis & Rosa (1991) method gives:

$$icf(\mathrm{Cl}^{++})^{\mathrm{MR91}} = 12.35, \tag{31}$$

yielding $\log \mathrm{Cl/O} = -2.81$, a much higher value than our adopted value.

Argon. A lower limit to the total argon abundance is given by: $\log \mathrm{Ar/O} > \log(\mathrm{Ar}^{++} + \mathrm{Ar}^{3+}/\mathrm{O})_{\mathrm{obs}} = -2.43$. However, a correction should be made in order to account for the presence of a small fraction of Ar^+. The equation based on the photoionization model gives:

$$\frac{\mathrm{Ar}}{\mathrm{O}} = \left(\frac{\mathrm{Ar}^{+}+\mathrm{Ar}^{++}}{\mathrm{O}^{++}}\right)_{\mathrm{obs}} \times \left(\frac{\mathrm{O}^{++}}{\mathrm{O}}\,\frac{\mathrm{Ar}}{\mathrm{Ar}^{+}+\mathrm{Ar}^{++}}\right)_{\mathrm{LPL99}}, \tag{32}$$

yielding $\log \mathrm{Ar/O} = -2.38$. This number can be compared to the prediction based on the Mathis & Rosa (1991) method:

$$icf(\mathrm{Ar}^{++}) = \left(\frac{\mathrm{Ar}}{\mathrm{Ar}^{++}}\right)_{\mathrm{MR91}} = 7.62, \tag{33}$$

implying $\log \mathrm{Ar/O} = -1.67$, which is very large, probably meaning that the Ar^{++} fraction for this object is underestimated by the method of Mathis & Rosa (1991).

5. DISCUSSION AND CONCLUSIONS

We have described new high-resolution spectroscopic data obtained for the two giant H II regions NGC 5461 and NGC 5471 in M101. We have determined five independent temperatures and four independent densities, as well as the abundances for the following elements: H, He, N, O, Ne, S, Cl, and Ar.

The densities obtained from the forbidden lines are considerably higher than the root mean square densities, implying strong density fluctuations with typical values of 0.01 for the filling factor.

The [Ar IV] density for NGC 5471 seems to be larger than N_e(O II); since the [Ar IV] lines originate close to the main ionizing sources, this finding probably indicates that the main ionizing stars are still located in a higher than average density region. A similar result was obtained for NGC 2363 by Pérez, González-Delgado, & Vílchez (2001) and Esteban et al. (2002).

A detailed comparison of the observed line intensities with those predicted by the photoionization model of Luridiana & Peimbert (2001) for NGC 5461 was made. We found that the observed [O I] line intensities are higher than predicted by the model, indicating that the object is ionization bounded. A similar argument can be made based on the [S II] lines.

The *icf*(N^+) for NGC 5461 derived from the photoionization model of Luridiana & Peimbert (2001) is about a factor of two higher than that derived by Mathis & Rosa (1991) and also about a factor of two higher than that derived from the empirical relationship given by $N^+/O^+ = N/O$. Further analysis is needed to understand the origin of this discrepancy.

The *icf*(Ne^{++}) for NGC 5461 derived from the photoionization model of Luridiana & Peimbert (2001) is about a factor of two higher than that derived by Mathis & Rosa (1991) and also about a factor of two higher than that derived from the empirical relationship given by $Ne^{++}/O^{++} = Ne/O$ (Peimbert & Costero 1969). In this case we think that the problem lies with the model by Luridiana & Peimbert (2001) for the following reasons: (a) probably the best determination for the Ne/O ratio of any H II region is that derived by Peimbert et al. (1992) for M17, amounting to -0.71 dex, (b) we expect the Ne/O abundance to be practically the same for NGC 5461, NGC 5471, and M17 because, to a very good first approximation, these elements are formed by massive stars and are ejected into the interstellar medium by supernovae of type II, and (c) the *icf*(Ne^{++}) for NGC 5471 and M17 are considerably smaller than for NGC 5461 indicating that the abundances for the first two objects are more reliable than for NGC 5461. The large Ne/O value derived for NGC 5461 is probably an upper limit due to the presence of the charge-exchange reaction $O^{++} + H^0 \rightarrow O^+ + H^+$ that allows some O^+ to coexist with Ne^{++}; this effect will reduce the *icf*(Ne^{++}) predicted by the model (see Peimbert, Luridiana, & Torres-Peimbert 1995, and references therein).

For NGC 5471, the ionization correction factors were computed based on a photoionization model for a similar H II region. Comparison of the total chemical abundances obtained to those implied by the Mathis & Rosa (1991) method highlighted sensitive discrepancies, particularly in the case of chlorine and argon. The origin of these discrepancies requires further study.

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