

# Faint emission lines in the Galactic H II regions M16, M20 and NGC 3603 <sup>\*</sup>

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## ABSTRACT

We present deep echelle spectrophotometry of the Galactic H II regions M16, M20 and NGC 3603. The data have been taken with the Very Large Telescope Ultraviolet-Visual Echelle Spectrograph in the 3100 to 10400 Å range. We have detected more than 200 emission lines in each region. Physical conditions have been derived using different continuum and line intensity ratios. We have derived He<sup>+</sup>, C<sup>++</sup> and O<sup>++</sup> abundances from pure recombination lines as well as abundances from collisionally excited lines for a large number of ions of different elements. We have obtained consistent estimations of the temperature fluctuation parameter,  $t^2$ , using different methods. We also report the detection of deuterium Balmer lines up to D $\delta$  (M16) and to D $\gamma$  (M20) in the blue wings of the hydrogen lines, which excitation mechanism seems to be continuum fluorescence. The temperature fluctuations paradigm agree with the results obtained from optical CELs and the more uncertain ones from far IR fine structure CELs in NGC 3603, although, more observations covering the same volume of the nebula are necessary to obtain solid conclusions.

**Key words:** ISM:abundances – H II regions– ISM:individual: M16, M20, NGC 3603

## 1 INTRODUCTION

Spectrophotometric studies of Galactic H II regions provide paramount information for the study of the chemical evolution of our galaxy. The use of echelle spectrographs at large aperture telescopes is a step ahead in the knowledge of the physics and chemical composition of these objects. In the last years, our group and others have obtained deep intermediate and high resolution optical spectra of bright Galactic H II regions (e.g. Peimbert, Storey & Torres-Peimbert 1993; Esteban et al. 1998, 1999a,b, 2004; García-Rojas et al. 2004, 2005; Tsamis et al. 2003), and extragalactic H II regions (e.g. Esteban et al. 2002; Peimbert 2003; Tsamis et al. 2003). These observations have permitted to obtain accurate measurements of very faint recombination lines (hereinafter RLs) of heavy element ions (especially C II and O II

lines) avoiding the problem of line blending. A common result of all the studies commented above is that the abundance determinations from RLs are systematically larger than those obtained using the standard methods based on the standard analysis of collisionally excited lines (hereinafter CELs). The discrepancies can be of the order of a factor 2-3. This problem may be related to the so-called temperature fluctuations suggested to be present in ionised nebulae (Torres-Peimbert, Peimbert & Daltabuit 1980). In fact, the intensity of CELs is much more strongly dependent on the temperature than RLs. This implies that RLs should be, in principle, more precise indicators of the true chemical abundances of the nebula. Nonetheless, this is still a controversial matter that has not been solved; in fact, alternative causes have been proposed recently, such as e.g. small-scale chemical inhomogeneities (Tsamis et al. 2003; Tsamis & Péquignot 2005).

This paper presents results of Very Large Telescope (VLT) spectrophotometry obtained with the Ultraviolet-Visual Echelle Spectrograph (UVES) of three bright H II

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regions: M16, M20 and NGC 3603. Our dataset, of an unprecedented quality, allows us to derive, with high precision, physical conditions and ionic abundances of many heavy elements and, for the first time in the three H II regions studied in this paper, C<sup>++</sup> and O<sup>++</sup> abundances from pure recombination lines.

M16 –*the Aquila nebula*, NGC 6611– is a well known H II region of our galaxy. Several works about star formation in the “elephant trunks” have appeared in the last years, most of them related to the evaporating gaseous globules (EGGs) discovered in this object (Hester et al. 1996; Thompson, Smith & Hester 2002; McCaughrean & Andersen 2002). In particular, recent near-infrared observations have led some authors to suggest that the epoch of star formation in M16 may be near its endpoint (Thompson, Smith & Hester 2002; McCaughrean & Andersen 2002). Surprisingly, there are only a few optical spectrophotometric works on the chemical composition of this object, computing the most common abundance ratios (Hawley 1978; Rodríguez 1999b; Deharveng et al. 2000).

M20 –*the Trifid nebula*, NGC 6514– is a nearby, small and symmetrical H II region ionised by the O7 V star HD 164492A. Although many works have been carried out to understand its kinematics (e.g. Bohuski 1973a; Rosado et al. 1999) and its temperature and density structure (e.g. Bohuski 1973b; Dopita 1974; Copetti et al. 2000), there is only a handful of studies devoted to the chemical composition of this nebula. Hawley (1978) and Rodríguez (1999b) derived heavy element abundances for M20 from spectrophotometric data. Lynds & O’Neil (1985) used long-slit spectroscopic data and narrow-band photometry to measure the intensities of several bright emission lines across the nebula, and derived He, N, O and S abundances for M20 through the computing of a dusty model. Additionally, because of the particular shape, size and dust distribution of this nebula some works were carried out to explore the interaction between gas and dust in this region (e.g. Krishna Swamy & O’Dell 1967).

Finally, NGC 3603 is the only optically visible, giant H II region in our Galaxy (Goss & Radhakrishnan 1969; Balick, Boeshaar & Gull 1980). The study of the physical properties of this object is crucial for the knowledge of physical processes in large H II regions. Many efforts have been developed on the study of the star formation and the stellar content of NGC 3603 (e.g. Brandl et al. 1999; Stolte et al. 2004) and on the study of its kinematics (e.g. Balick, Boeshaar & Gull 1980; Clayton 1986, 1990; Nürnberger et al. 2002), but few works have studied the chemical properties of the ionised gas of this object using optical data (Melnick, Tapia & Terlevich 1989; Girardi et al. 1997; Tapia et al. 2001) and mid and far-infrared data (Lacy, Beck & Geballe 1982; Simpson et al. 1995).

In §§ 2 and 3 we describe the observations, the data reduction procedure and the measurement and identification of the emission lines. In § 4 we calculate electron temperatures and densities using several diagnostic ratios and discuss the  $t^2$  results. In § 5 ionic abundances are determined based on both kinds of lines: CELs and RLs. Total abundances are determined in § 6. Deuterium Balmer lines and their excitation mechanism are discussed in § 7. The detection of velocity components in NGC 3603 is reported in § 8.

**Table 1.** Journal of observations.

Date	$\Delta\lambda$ (Å)	Exp. time (s)		
		M20	M16	NGC 3603
2003/03/29-31	3000–3900	3×600	3×900	3×600
	3800–5000	3×1800	3×1825	60, 3×1320
	4750–6800	3×600	3×900	3×600
	6700–10400	3×1800	3×1825	60, 3×1320

Finally, in §§ 9 and 10 we present the general discussion and the conclusions, respectively.

## 2 OBSERVATIONS AND DATA REDUCTION

The observations were made on 2003 March 29, 30 and 31 with UVES (D’Odorico et al. 2000), at the VLT Kueyen Telescope in Cerro Paranal Observatory (Chile). We used the standard settings in both the red and blue arms of the spectrograph, covering the spectral region from 3100 to 10400 Å. The log of the observations is presented in Table 1.

The wavelength regions 5783–5830 Å and 8540–8650 Å were not observed due to a gap between the two CCDs used in the red arm. There are also five small gaps that were not observed, 9608–9612 Å, 9761–9767 Å, 9918–9927 Å, 10080–10093 Å and 10249–10264 Å, because the five redmost orders did not fit completely within the CCD.

The slit was oriented east-west in all the cases and the atmospheric dispersion corrector (ADC) was used to keep the same observed region within the slit regardless of the air mass value. The slit width was set to 3'' and the slit length was set to 10'' in the blue arm and to 12'' in the red arm; the slit width was chosen to maximize the S/N ratio of the emission lines and to maintain the required resolution to separate most of the weak lines needed for this project. The effective resolution at a given wavelength is approximately  $\Delta\lambda \sim \lambda/8800$ .

The centre of the slit was placed 48'' north and 40'' west of BD-13 4930, for M16; 17'' north and 10'' east of HD164492, for M20; and 12'' north and 116'' east of HD 306201, for NGC 3603. All slit positions cover very bright zones of the nebulae. The final usable one-dimensional spectra were extracted from an area of 3''×8.5'' for all the objects.

The spectra were reduced using the IRAF<sup>1</sup> echelle reduction package, following the standard procedure of bias subtraction, aperture extraction, flatfielding, wavelength calibration and flux calibration. The standard stars EG 247, C-32d9927 (Hamuy et al. 1992, 1994) and HD 49798 (Turnshek et al. 1990; Bohlin & Lindler 1992) were observed for flux calibration.

## 3 LINE INTENSITIES AND REDDENING CORRECTION

Line intensities were measured integrating all the flux in the line between two given limits and over a local continuum

<sup>1</sup> IRAF is distributed by NOAO, which is operated by AURA, under cooperative agreement with NSF.

estimated by eye. In the cases of line blending, a multiple Gaussian profile fit procedure was applied to obtain the line flux of each individual line. These measurements were made with the SPLOT routine of the IRAF package. In some cases of very tight blends or blends with very bright telluric lines the analysis was performed via Gaussian fitting (or Voigt profiles in the case of sky emission lines) making use of the Starlink DIPSO software (Howard & Murray 1990). Also, DIPSO was used to obtain the best values for the fluxes of most of the H I Balmer lines in M20, which were affected by absorptions associated to the stellar continuum scattered light. For each single or multiple Gaussian fit, DIPSO gives the fit parameter (radial velocity centroid, Gaussian sigma, FWHM, etc.) and their associated statistical errors.

Table 2 presents the emission line intensities measured in the three H II regions. The first and fourth columns include the adopted laboratory wavelength,  $\lambda_0$ , and the observed wavelength in the heliocentric restframe,  $\lambda_{\text{obs}}$ . The second and third columns include the ion and the multiplet number, or series for each line. The fifth and sixth columns list the observed flux relative to H $\beta$ ,  $F(\lambda)$ , and the reddening corrected flux relative to H $\beta$ ,  $I(\lambda)$ . The seventh column includes the fractional error ( $1\sigma$ ) in the line intensities. Errors were derived following (García-Rojas et al. 2004), adding quadratically the error due to flux calibration that has been estimated to be about 3%, which corresponds to the standard deviation obtained from the calibration curves of the three standard stars.

A total of 256, 261 and 235 emission lines were measured in M16, M20 and NGC 3603, respectively. Most of the lines are permitted lines. We have measured 54 forbidden lines (CELs) in M16, 58 in M20 and 60 in NGC 3603. We have detected several semiforbidden lines: 8 in M16, 12 in M20, and only 2 in NGC 3603 (see Table 2). Four lines detected in NGC 3603 were identified as red velocity components of highly ionised species (see § 8 for a detailed discussion on these lines). In several cases some identified lines were severely blended with telluric lines, making impossible their measurement. Other lines were strongly affected by atmospheric features in absorption or by internal reflections by charge transfer in the CCD, rendering their intensities unreliable. Also, several lines were labelled as dubious identifications and two emission lines could not be identified in any of the available references. All those lines are indicated in Table 2.

The identification and adopted laboratory wavelengths of the lines were obtained following several previous identifications in the literature (see García-Rojas et al. 2004; Esteban et al. 2004, and references therein). Several identifications labelled as dubious in García-Rojas et al. (2004, 2005) have been updated in this work following a criteria based in the comparison of the radial velocity of the line with lines of similar ionisation potential.

We have assumed the standard dust extinction law for the Milky Way ( $R_v=3.1$ ) parametrized by Seaton (1979) for M20 and NGC 3603. A reddening coefficient of  $c(H\beta)=0.36\pm 0.04$  was determined for M20, by fitting the observed  $I(\text{H Balmer lines})/I(H\beta)$  ratios (from H16 to H $\beta$ ) and  $I(\text{H Paschen lines})/I(H\beta)$  (from P22 to P7), to the theoretical ones computed by Storey & Hummer (1995) for  $T_e = 10000$  K and  $n_e = 1000 \text{ cm}^{-3}$  (see below). H I lines af-

**Table 2.** Observed and reddening-corrected relative line fluxes  $F(\lambda)$  and  $I(\lambda)$  respectively, in units such that  $F(H\beta)=100$ .

$\lambda_0$ (Å)	Ion	Mult.	$\lambda_{\text{obs}}$ (Å)	$F(\lambda)$	$I(\lambda)^a$	err (%) <sup>b</sup>	Notes
<b>M 16</b>							
3187.84	He I	3	3187.81	0.693	1.352	6	
3354.42	He I	8	3354.64	0.146	0.276	18	
3347.59	He I	7	3447.65	0.201	0.375	14	
3554.42	He I	34	3554.45	0.219	0.401	13	
3587.28	He I	32	3587.37	0.178	0.325	15	
3613.64	He I	6	3613.71	0.250	0.453	12	
3634.25	He I	28	3634.30	0.383	0.691	8	
3660.28	H I	H32	3660.41	0.112	0.200	23	
3661.22	H I	H31	3661.27	0.162	0.290	17	
3662.26	H I	H30	3662.33	0.213	0.381	13	
3663.40	H I	H29	3663.50	0.217	0.388	13	
3664.68	H I	H28	3664.73	0.210	0.376	13	
3666.10	H I	H27	3666.15	0.259	0.464	11	
3667.68	H I	H26	3667.77	0.253	0.453	12	
3669.47	H I	H25	3669.57	0.322	0.575	10	
3671.48	H I	H24	3671.56	0.362	0.646	9	
3673.76	H I	H23	3673.86	0.398	0.710	8	
3676.37	H I	H22	3676.44	0.398	0.711	8	
3679.36	H I	H21	3679.43	0.434	0.774	8	
3682.81	H I	H20	3682.89	0.434	0.772	8	
3686.83	H I	H19	3686.91	0.565	1.005	7	
3691.56	H I	H18	3691.62	0.594	1.054	6	
3697.15	H I	H17	3697.24	0.684	1.213	6	
3703.86	H I	H16	3703.94	0.804	1.423	5	
3705.04	He I	25	3705.10	0.378	0.669	9	
3711.97	H I	H15	3712.05	0.972	1.715	5	
3721.94	[S III]	2F	3721.96	1.679	2.955	4	
3721.94	H I	H14					
3726.03	[O II]	1F	3726.16	88.191	154.979	4	
3728.82	[O II]	1F	3728.91	69.245	121.581	4	
3734.37	H I	H13	3734.46	1.580	2.770	4	
3750.15	H I	H12	3750.24	2.014	3.511	4	
3770.63	H I	H11	3770.72	2.503	4.336	4	
3797.90	H I	H10	3797.98	3.424	5.874	4	
3819.61	He I	22	3819.70	0.653	1.112	6	
3835.39	H I	H9	3835.47	4.845	8.197	4	
3856.02	Si II	1	3856.07	0.126	0.211	10	
3856.12	O II	12					
3862.59	Si II	1	3862.59	0.080	0.133	14	
3867.48	He I	20	3867.54	0.077	0.129	14	
3868.75	[Ne III]	1F	3868.81	2.162	3.612	4	
3871.82	He I	60	3871.82	0.065	0.109	16	
3888.65	He I	2	3889.00	11.284	18.687	3	
3889.05	H I	H8					
3918.98	C II	4	3918.92	0.084	0.138	13	
3920.68	C II	4	3920.73	0.099	0.162	12	
3926.53	He I	58	3926.64	0.087	0.141	13	
3964.73	He I	5	3964.81	0.530	0.849	4	
3967.46	[Ne III]	1F	3967.52	0.681	1.090	4	
3970.07	H I	H7	3970.15	10.591	16.928	3	
4009.22	He I	55	4009.30	0.132	0.207	9	
4026.08	N II	40	4026.28	1.276	1.987	3	
4026.21	He I	18					
4068.60	[S II]	1F	4068.72	2.264	3.452	3	
4076.35	[S II]	1F	4076.47	0.898	1.364	4	
4100.62	D I	D6	4100.76	0.015	0.022	:	
4101.74	H I	H6	4101.82	17.800	26.689	3	















$c(\text{H}\beta)=0.45$  from long slit spectroscopic data for a larger extension of the nebula.

Following the same method as for M20, we have derived  $c(\text{H}\beta)=2.36\pm 0.06$  for NGC 3603. Tapia et al. (2001) derived a  $c(\text{H}\beta)=2.51$  for a slit position  $116''$  east and  $12''$  north from our slit position. Melnick, Tapia & Terlevich (1989) derived an average  $c(\text{H}\beta)=1.93$  for four slit positions. Girardi et al. (1997) obtained  $c(\text{H}\beta)=2.36$  and  $2.59$  for two slit positions in NGC 3603 located near ours and using the extinction law of Savage & Mathis (1979). Even though the different extinction laws used are different, these values of  $c(\text{H}\beta)$  are in very good agreement with our value. Using the extinction law by Savage & Mathis (1979) we have obtained  $c(\text{H}\beta)=2.29\pm 0.06$  which is consistent with our adopted value.

On the other hand, Chini & Wargau (1990) confirmed an abnormal extinction of dense interstellar dust within M16 from photometric observations of the associated young stellar cluster NGC 6611. They found that deviations from the normal extinction law occur at wavelengths shorter than  $5500 \text{ \AA}$ , because of the higher size of the graphite grains. Following those authors we have assumed the extinction law parametrized by Cardelli, Clayton & Mathis (1989) with the ratio of total to selective extinction,  $R_v=3.1$  for wavelengths higher than  $5500 \text{ \AA}$ , and  $R_v=4.8$  for shorter wavelengths. From this extinction law and following the same procedure than for M20 and NGC 3603, we have derived  $c(\text{H}\beta)=1.21\pm 0.06$  for M16, assuming  $T_e = 8000 \text{ K}$  and  $n_e = 1000 \text{ cm}^{-3}$  (Rodríguez 1998).

## 4 PHYSICAL CONDITIONS

### 4.1 Temperatures and Densities

The large number of emission lines identified and measured in the spectra allows us to derive physical conditions using different emission line ratios. The temperatures and densities are presented in Table 3. Most of the determinations were carried out with the IRAF task TEMDEN of the package NEBULAR (Shaw & Dufour 1995).

The methodology followed for the derivation of  $n_e$  and  $T_e$ , and the atomic data compilation used have been described in previous papers (i.e. García-Rojas et al. 2004, 2005). In the case of electron densities, ratios of CELs of several ions have been used. We have derived the  $[\text{Fe III}]$  density from the intensity of the brightest lines (which have errors equal or smaller than 30 % and that seem not to be affected by line blending, see Table 2) together with the computations of Rodríguez (2002). We have used 4, 6 and 4  $[\text{Fe III}]$  lines for M16, M20 and NGC 3603 respectively; the methodology consisted of adopting the density that minimized the dispersion of individual  $\text{Fe}^{++}/\text{H}^+$  abundance ratios. All the computed values of  $n_e$  are consistent within the errors (see Table 3).

A weighted mean of  $n_e(\text{O II})$ ,  $n_e(\text{Fe III})$ ,  $n_e(\text{Cl III})$  and  $n_e(\text{S II})$  has been used to derive  $T_e(\text{N II})$ ,  $T_e(\text{O II})$ ,  $T_e(\text{S II})$ ,  $T_e(\text{O III})$ ,  $T_e(\text{Ar III})$  and  $T_e(\text{S III})$ , and we iterated until convergence. For M20, which has a low ionisation degree, this is the first time that it has been possible to derive temperatures associated with high-ionised species. The values adopted for  $n_e$  are shown in Table 3. We have excluded  $n_e(\text{N I})$  from the average because this ion is representative

of the very outer part of the nebula, and does not coexist with the other ions.

Electron temperatures have been derived from the ratio of CELs of several ions and making use of NEBULAR routines with upgraded atomic data for  $[\text{S III}]$  (see García-Rojas et al. 2005).

We have corrected  $T_e(\text{O II})$  for the contribution to  $\lambda\lambda 7320+7330$  due to recombination following the formula derived by Liu et al. (2001) (their equation 2). From our O II recombination lines we have estimated contributions of about 3%, 2% and 7% for M16, M20 and NGC 3603, respectively.

Also, the contribution to the intensity of the  $[\text{N II}] \lambda 5755$  line due to recombination can be estimated from an expression given by Liu et al. (2001) (their equation 1). From our data, we have obtained a contribution of recombination of about 2%, for M16 and NGC 3603, that does not affect significantly the temperature determination. For M20, the derived contribution was less than 0.1 %, which is absolutely negligible<sup>2</sup>.

Figure 1 shows the spectral regions near the Balmer and the Paschen limits. The discontinuities can be clearly appreciated, except in the case of the Balmer limit in NGC 3603. Discontinuities are defined as  $I_c(\text{Bac}) = I_c(\lambda 3646^-) - I_c(\lambda 3646^+)$  and  $I_c(\text{Pac}) = I_c(\lambda 8203^-) - I_c(\lambda 8203^+)$  respectively. The high spectral resolution of the spectra permits to measure the continuum emission in zones very near de discontinuity, minimizing the possible contamination of other continuum contributions. In fact, on the blue part of Paschen discontinuity, we have selected a zone that is free of contamination by telluric absorption. That zone is between  $8203$  and  $8209 \text{ \AA}$ . The uncertainty in the derived continua is the standard mean deviation of the averaged continua. On the red part, the measurement of the continuum is much easier, and could be computed as an average of the continua between the closest Paschen lines. We have obtained power-law fits to the relation between  $I_c(\text{Bac})/I(\text{H}n)$  or  $I_c(\text{Pac})/I(\text{P}n)$  and  $T_e$  for different  $n$  corresponding to different observed lines of both series. The emissivities as a function of electron temperature for the nebular continuum and the H I Balmer and Paschen lines have been taken from Brown & Mathews (1970) and Storey & Hummer (1995), respectively. The  $T_e(\text{Bac})$  adopted is the average of the values using the lines from  $\text{H}\alpha$  to H 10 (the brightest ones). In the case of  $T_e(\text{Pac})$ , the adopted value is the average of the individual temperatures obtained using the lines from P 7 to P 13 (the brightest lines of the series), excluding those lines whose intensity seems to be affected by telluric lines or sky absorption. To our knowledge this is the first time that Balmer and Paschen temperatures have been derived for these three nebulae.

We have compared our averaged  $T_e(\text{H I})$  with those derived from radio H I recombination lines. Caswell & Haynes (1987) obtained  $T_e(\text{H I}) = 6900 \text{ K}$  for NGC 3603, the same

<sup>2</sup> Although the formation mechanism of N II permitted lines is mostly resonance fluorescence by the recombination line He I  $\lambda 508.64 \text{ \AA}$  (Grandi 1976), we have estimated  $\text{N}^{++}/\text{H}^+$  abundances from N II lines of multiplet 3, which is less affected by such effects. Anyway, the correction is in all the cases very small, and effects due to resonance fluorescence do not modify the derived temperature by more than 100 K.

**Table 3.** Plasma Diagnostic.

Parameter	Line	Value		
		M16	M20	NGC 3603
$n_e$ ( $\text{cm}^{-3}$ )	[N I] ( $\lambda 5198$ )/( $\lambda 5200$ )	$1100^{+750}_{-400}$	$560^{+340}_{-220}$	4000:
	[O II] ( $\lambda 3726$ )/( $\lambda 3729$ )	$1050 \pm 250$	$240 \pm 70$	$2300 \pm 750$
	[O II] ( $\lambda 3726+\lambda 3729$ )/( $\lambda 7320+\lambda 7330$ ) <sup>a</sup>			$5300 \pm 850$
	[S II] ( $\lambda 6716$ )/( $\lambda 6731$ )	$1390 \pm 550$	$320 \pm 130$	$4150^{+3350}_{-1650}$
	[Fe III]	$540^{+>1000}_{-500}$	$560 \pm 390$	1330:
	[Cl III] ( $\lambda 5518$ )/( $\lambda 5538$ )	$1370 \pm 1000$	$350^{+780}_{-350}$	$5600^{+3900}_{-2400}$
	[Ar IV] ( $\lambda 4711$ )/( $\lambda 4740$ )	—	—	$\leq 4000$
	$n_e$ (adopted)	$1120 \pm 220$	$270 \pm 60$	$5150 \pm 750$
$T_e$ (K)	[N II] ( $\lambda 6548+\lambda 6583$ )/( $\lambda 5755$ ) <sup>a</sup>	$8450 \pm 270$	$8500 \pm 240$	$11050 \pm 800$
	[S II] ( $\lambda 6716+\lambda 6731$ )/( $\lambda 4069+\lambda 4076$ )	$7520 \pm 430$	$6950 \pm 350$	$11050^{+3550}_{-2050}$
	[O II] ( $\lambda 3726+\lambda 3729$ )/( $\lambda 7320+\lambda 7330$ ) <sup>a</sup>	$8260 \pm 400$	$8275 \pm 400$	$12350 \pm 1250$
	$T_e$ (low)	$8350 \pm 200$	$8400 \pm 200$	$11400 \pm 700$
	[O III] ( $\lambda 4959+\lambda 5007$ )/( $\lambda 4363$ )	$7650 \pm 250$	$7800 \pm 300$	$9060 \pm 200$
	[Ar III] ( $\lambda 7136+\lambda 7751$ )/( $\lambda 5192$ )	—	$8730 \pm 920^b$	—
	[S III] ( $\lambda 9069+\lambda 9532$ )/( $\lambda 6312$ )	$8430 \pm 450$	$8300 \pm 400$	$8800 \pm 500$
	$T_e$ (high)	$7850 \pm 220$	$7980 \pm 250$	$9030 \pm 200$
	He I	$7300 \pm 350$	$7650 \pm 300$	$8480 \pm 200$
	Balmer decrement	$5450 \pm 820$	$6000 \pm 1300$	—
	Paschen decrement	$7200 \pm 1300$	$5700 \pm 1300$	$6900 \pm 1100$

<sup>a</sup> The recombination contribution to the auroral lines has been taken into account (see text)

<sup>b</sup> The [Ar III]  $\lambda 7751$  line is severely blended with a telluric line.

value we derive for the Paschen temperature of this object; Reifenstein et al. (1970) derived  $T_e(\text{H I}) = 6100 \pm 1500$  K for M16 from the H109 $\alpha$  radio recombination line, which is also in good agreement with our average temperature; however, for M20, Reifenstein et al. (1970) derived  $T_e(\text{H I}) = 7300 \pm 2500$ , which is higher than the  $T_e(\text{H I})$  we obtain, although it is compatible within the errors. Effects of scattered continuum light in the continua of Balmer and Paschen limits may be a reason of this discrepancy (see § 9.1.1). However, aperture effects cannot be ruled out. Radio determinations usually refer to average values over large extensions of the nebula, instead our values refer to very small and particular zones of the nebulae. Another interesting comparison is with  $T_e(\text{H I})$  derived through radio continuum measurements. Shaver & Goss (1970) estimate  $T_e(\text{H I}) = 6800 \pm 700$  K for NGC 3603, from 408 Mhz continuum measurements, which is in excellent agreement with the estimate through radio H I recombination lines and our own spectroscopic value.

Peimbert, Peimbert & Luridiana (2002) developed a method to derive the helium temperature,  $T_e(\text{He I})$ , in the presence of temperature fluctuations. Assuming a 2-zone ionization scheme and the formulation of Peimbert, Peimbert & Luridiana (2002) we have derived  $T_e(\text{He I}) = 7300 \pm 350$  K,  $7650 \pm 300$  and  $8480 \pm 200$  for M16, M20 and NGC 3603, respectively. These results are higher than those derived from H I.

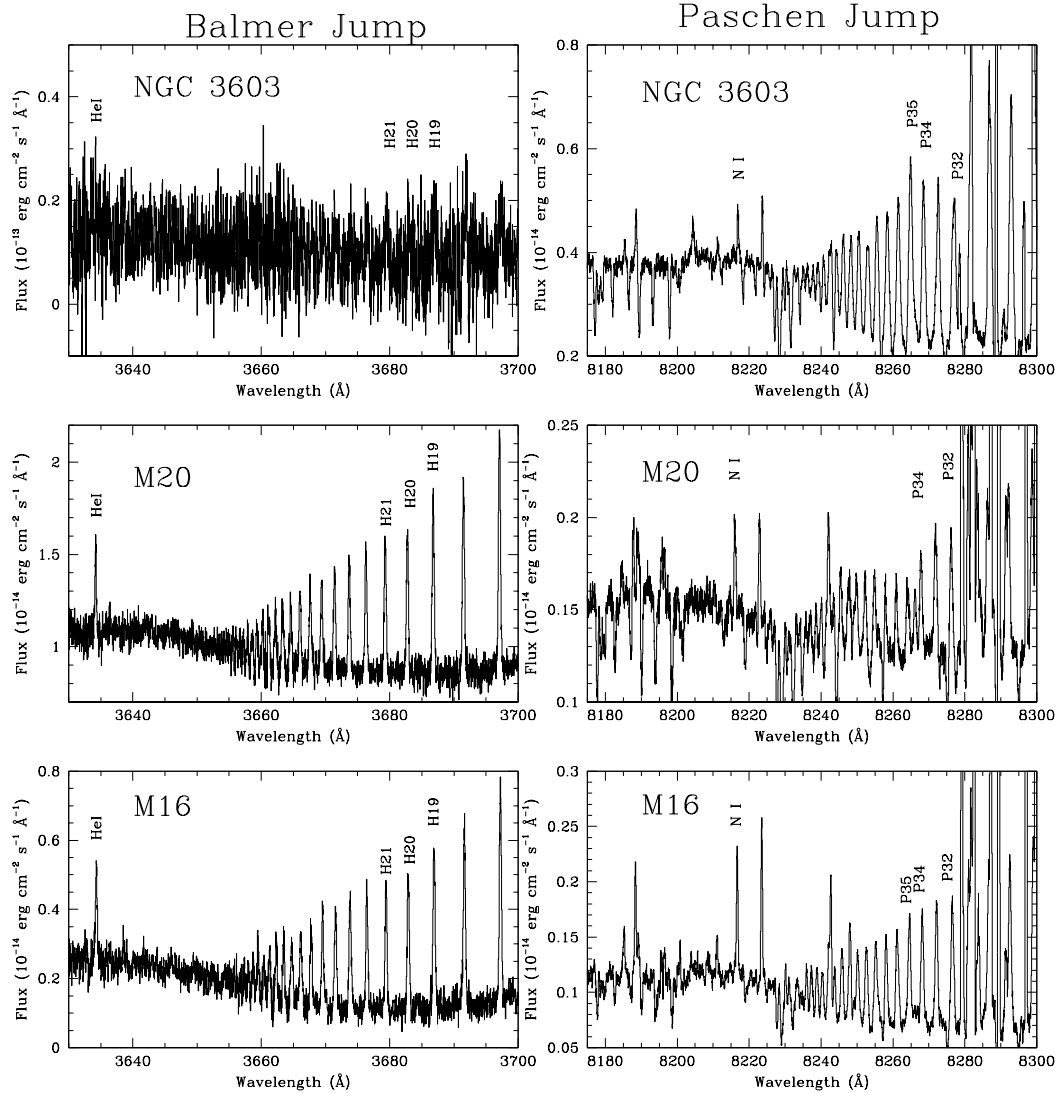
We have assumed a 2-zone ionisation scheme for the calculation of ionic abundances (see § 5). We have adopted the average of electron temperatures obtained from [N II] and [O II] lines as representative for the low ionisation zone designated  $T_e(\text{low})$ . The average of electron temperatures obtained from [O III] and [S III] lines has been assumed as rep-

resentative of the high ionisation zone designated  $T_e(\text{high})$  (see Table 3).

## 4.2 Temperature variations

Torres-Peimbert, Peimbert & Daltabuit (1980) proposed the presence of spatial temperature fluctuations (parametrized by  $t^2$ ) as the cause of the discrepancy between abundance calculations based on CELs and RLs. This is due to the different dependence on the electron temperature of the CELs and RLs emissivities. Assuming the validity of the temperature fluctuations paradigm, the comparison of the abundances determined from both kinds of lines for a given ion should provide an estimation of  $t^2$ . Also, Peimbert (1971) proposed that there is a dichotomy between  $T_e$  derived from the [O III] lines and from the hydrogen recombination continuum discontinuities, which is correlated with the discrepancy between CEL and RL abundances (e.g. Peimbert & Costero 1969; Torres-Peimbert, Peimbert & Daltabuit 1980; Liu et al. 2000; Tsamis et al. 2004), so the comparison between electron temperatures obtained from both methods is an additional indicator of  $t^2$ . A complete formulation of temperature fluctuations has been developed by Peimbert (1967), Peimbert & Costero (1969) and Peimbert (1971) (see also Peimbert, Peimbert & Luridiana 2002; Ruiz et al. 2003). Esteban (2002) discussed some of the different mechanisms proposed to explain the presence of temperature fluctuations in nebulae, it is beyond the scope of the present paper to treat this topic.

As we have assumed a two-zone ionisation scheme, we have followed the re-formulation proposed by Peimbert, Peimbert & Ruiz (2000) and Peimbert, Peimbert & Luridiana (2002) to derive the value



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**Figure 1.** Section of the echelle spectra of the three nebulae including the Balmer (left) and the Paschen (right) limits (observed fluxes).

of  $t^2$  comparing the average of  $T_e(Bac)$  and  $T_e(Pac)$  with the combination of  $T_e([O II])$  and  $T_e([O III])$ ,  $T_e(O II+III)$ , using equation (A1) of Peimbert, Peimbert & Luridiana (2002). In Table 4 we include the different  $t^2$  values that produce the agreement between the abundance determinations obtained from CELs and RLs of  $O^+$  (for those objects where  $O I$  RLs have been measured) and  $O^{++}$ , as well as the values of  $t^2$  obtained from the combination of  $T_e(O II+III)$  and the average value of  $T_e(Bac)$  and  $T_e(Pac)$ . As it can be seen, the different  $t^2$  values obtained are rather consistent. In Table 4, we also include the  $t^2$  value obtained from the application of a maximum likelihood method to search for the physical conditions, including  $He^+/H^+$  ratios and optical depths, that would be a simultaneous fit to all the measured lines of  $He I$  (see § 5.1). Finally, in Table 4 we show the final adopted values, which are error-weighted averages.

**Table 4.**  $t^2$  parameter

Method	$t^2$		
	M16	M20	NGC 3603
$O^{++}$ (R/C)	$0.046 \pm 0.007$	$0.038 \pm 0.016$	$0.042 \pm 0.009$
$O^+$ (R/C)	—	$0.032 \pm 0.020$	—
$He^+$	$0.017 \pm 0.013$	$0.017 \pm 0.010$	$0.032 \pm 0.014$
Bac/Pac-FL	$0.045 \pm 0.014$	$0.049 \pm 0.019$	$0.056 \pm 0.023$
Adopted	$0.039 \pm 0.006$	$0.029 \pm 0.007$	$0.040 \pm 0.008$

## 5 IONIC ABUNDANCES

### 5.1 $He^+$ abundance

We have measured 47, 53 and 64  $He I$  emission lines in the spectra of M16, M20 and NGC 3603, respectively. These lines arise mainly from recombination but they can be affected by collisional excitation and self-absorption effects.

**Table 5.** He<sup>+</sup> abundance.

Line	He <sup>+</sup> /H <sup>+</sup> <sup>a</sup>		
	M16	M20	NGC 3603
3819.61	827 ± 50	731 ± 44	1014 ± 314
3888.65	—	695 ± 21	—
3964.73	797 ± 32	749 ± 30	820 ± 90
4026.21	834 ± 25	756 ± 22	1043 ± 63
4387.93	777 ± 31	678 ± 41	1067 ± 107
4471.09	758 ± 23	690 ± 21	998 ± 30
4713.14	794 ± 32	674 ± 40	1001 ± 70
4921.93	757 ± 23	723 ± 22	926 ± 37
5875.64	761 ± 23	672 ± 19	921 ± 37
6678.15	751 ± 30	702 ± 28	911 ± 46
7065.28	781 ± 39	703 ± 28	956 ± 57
7281.35	831 ± 41	787 ± 39	957 ± 57
Adopted <sup>b</sup>	781 ± 12	711 ± 10	961 ± 17

<sup>a</sup> In units of 10<sup>-4</sup>, for  $\tau_{3889} = 2.99 \pm 0.85$ ,  $2.09 \pm 0.49$ , and  $12.12 \pm 1.00$ , and  $t^2 = 0.039 \pm 0.006$ ,  $0.029 \pm 0.007$  and  $0.040 \pm 0.008$  Uncertainties correspond to line intensity errors.

<sup>b</sup> It includes all the relevant uncertainties in emission line intensities,  $n_e$ ,  $\tau_{3889}$  and  $t^2$ .

We have determined the He<sup>+</sup>/H<sup>+</sup> ratio from a maximum likelihood method (e.g. Peimbert, Peimbert & Ruiz 2000), using the  $n_e$  given in Table 3 and  $T(\text{O II+III})=8130$  K for M16,  $T(\text{O II+III})=8200$  K for M20 and  $T(\text{O II+III})=9600$  K for NGC 3603 (see § 4.2). We have used the effective recombination coefficients of Storey & Hummer (1995) for H I and those of Smits (1996) and Benjamin, Skillman & Smits (1999) for He I. The collisional contribution was estimated from Sawey & Berrington (1993) and Kingdon & Ferland (1995), and the optical depth in the triplet lines were derived from the computations by Benjamin et al. (2002).

In Table 5 we have included the He<sup>+</sup>/H<sup>+</sup> ratios we have obtained for the individual He I lines not affected by line blending and with the highest signal-to-noise ratio. We have excluded He I  $\lambda 5015$  because it could suffer self-absorption effects from the 2<sup>1</sup>S metastable level, as was already pointed out by Esteban et al. (2004). We have also excluded  $\lambda 3889$  for M16 and NGC3603 because it is severely blended with the Balmer H8 line. We have performed a  $\chi^2$  optimisation of the values given in the table, and we have obtained a  $\chi^2$  parameter of 8.3, 15.1 and 9.63 for M16, M20 and NGC 3603, respectively, these values indicate a reasonable goodness of the fits for a system with nine degrees of freedom.

## 5.2 Ionic Abundances from CELs

Ionic abundances of N<sup>+</sup>, O<sup>+</sup>, O<sup>++</sup>, Ne<sup>++</sup>, S<sup>+</sup>, S<sup>++</sup>, Cl<sup>+</sup>, Cl<sup>++</sup>, Cl<sup>3+</sup> Ar<sup>++</sup> and Ar<sup>3+</sup> have been determined from CELs, using the IRAF package NEBULAR except for Cl<sup>+</sup> (see García-Rojas et al. 2004). Additionally, we have determined the ionic abundances of Fe<sup>++</sup>, which we will discuss further on. Ionic abundances are listed in Table 6 and correspond to the mean value of the abundances derived from all the individual lines of each ion observed (weighted by their relative strengths).

To derive the abundances for  $t^2 > 0.00$  (see § 4) we used the abundances for  $t^2 = 0.00$  and the formulation of by

Peimbert (1967) and Peimbert & Costero (1969). For other  $t^2$  values, it is possible to interpolate or extrapolate the values presented in Table 6.

Many [Fe II] lines have been identified in our spectra, but are severely affected by fluorescence effects (Rodríguez 1999a; Verner et al. 2000). The [Fe II]  $\lambda 8617$  Å line is almost insensitive to fluorescence effects, but unfortunately it is in one of our narrow observational gaps. We have also measured [Fe II]  $\lambda 7155$ , a line which does not seem to be affected by fluorescence effects (Rodríguez 1996). We have derived the Fe<sup>+</sup> abundance from this line assuming that  $I(\lambda 7155)/I(\lambda 8616) \sim 1$  (Rodríguez 1996) and using the calculations of Bautista & Pradhan (1996). We find Fe<sup>+</sup>/H<sup>+</sup>  $\sim 4.2 \times 10^{-8}$ ,  $3.2 \times 10^{-8}$  and  $1.1 \times 10^{-8}$  for M16, M20 and NGC 3603, respectively. In NGC 3603, the Fe<sup>+</sup> abundance is much lower than that of Fe<sup>++</sup> (see Table 6). Therefore, in what follows the Fe<sup>+</sup> abundance will be considered negligible for this object.

The calculations for Fe<sup>++</sup> have been done with a 34 level model-atom that uses the collision strengths of Zhang (1996) and the transition probabilities of Quinet (1996). We have used 5 [Fe III] lines for M16, 6 for M20 and 5 for NGC 3603, that do not seem to be affected by line-blending. The Fe<sup>++</sup> abundances are also included in Table 6.

## 5.3 Ionic Abundances from Recombination Lines

We have measured a large number of permitted lines of heavy element ions such as O I, O II, C I, C II, S II, N I, N II, Ar I, Si I, Si II, and Fe I many of them detected for the first time in these nebulae. Unfortunately, most permitted lines are affected by fluorescence effects or blended with telluric emission lines making their intensities unreliable. Detailed discussions on the mechanism of formation of the permitted lines can be found in Esteban et al. (1998, 2004, and references therein).

For the first time for these nebulae, we have been able to measure the ionic abundance ratios of O<sup>+</sup>/H<sup>+</sup>, O<sup>++</sup>/H<sup>+</sup> and C<sup>++</sup>/H<sup>+</sup> from pure recombination lines. We have computed the abundances using  $T_e(\text{Low})$  (for O<sup>+</sup>/H<sup>+</sup>),  $T_e(\text{High})$  (for O<sup>++</sup>/H<sup>+</sup> and C<sup>++</sup>/H<sup>+</sup>) and  $n_e$  from Table 3. Atomic data and methodology are the same than in García-Rojas et al. (2004). Although part of these ionic abundances were presented in a previous work of our group (Esteban et al. 2005), we give here the details of their derivation.

Eight permitted lines of C II have been measured in M16 and M20, and only five in NGC 3603. Lines of multiplets 6, 17.02 and 17.04 are  $3d - 4f$  transitions and are, in principle, excited by pure recombination (see Grandi 1976). Unfortunately, only multiplet 6 is usable because the lines of the other multiplets are affected by blending with atmospheric spectral features or CCD charge transfer effects, so we have adopted the C<sup>++</sup>/H<sup>+</sup> ratio given by that multiplet (see Table 7).

The O<sup>+</sup> abundance was derived from the O I  $\lambda 7771.94$  Å line, and was only reliable for M20, because the spectral zone of multiplet 1 is strongly affected by telluric lines. The abundance derived from this line is case independent and recombination is its formation mechanism because the line corresponds to a quintuplet transition, while the ground term of this ion is a triplet. The O<sup>+</sup>/H<sup>+</sup> ratios are presented in Table 8.

**Table 6.** Ionic abundances from collisionally excited lines<sup>a</sup>.

Ion	M16		M20		NGC 3603	
	$t^2=0.000$	$t^2=0.039\pm 0.006$	$t^2=0.000$	$t^2=0.029\pm 0.007$	$t^2=0.000$	$t^2=0.040\pm 0.008$
N <sup>0</sup>	6.15±0.06	6.33±0.07	5.90±0.07	6.03±0.08	5.65±0.11	5.75±0.11
N <sup>+</sup>	7.71±0.05	7.88±0.06	7.55±0.04	7.67±0.05	6.45±0.07	6.55±0.07
O <sup>0</sup>	7.23±0.05	7.40±0.06	6.60±0.05	6.72±0.06	6.32±0.09	6.42±0.09
O <sup>+</sup>	8.47±0.08	8.66±0.09	8.46±0.07	8.59±0.08	7.44±0.11	7.54±0.11
O <sup>++</sup>	7.85±0.07	8.18±0.10	7.67±0.08	7.90±0.10	8.42±0.05	8.68±0.08
Ne <sup>++</sup>	7.01±0.07	7.38±0.10	6.55±0.09	6.80±0.11	7.72±0.05	8.00±0.08
S <sup>+</sup>	6.32±0.05	6.49±0.06	6.17±0.05	6.29±0.06	5.09±0.10	5.18±0.10
S <sup>++</sup>	6.84±0.06	7.22±0.10	6.79±0.06	7.09±0.10	6.83±0.04	7.11±0.09
Cl <sup>+</sup>	4.77±0.05	4.91±0.07	4.75±0.05	4.85±0.07	3.46±0.07	3.54±0.07
Cl <sup>++</sup>	5.04±0.06	5.36±0.08	4.99±0.07	5.21±0.08	5.06±0.05	5.30±0.08
Cl <sup>3+</sup>	—	—	—	—	3.86±0.04	4.06±0.07
Ar <sup>++</sup>	6.25±0.05	6.53±0.08	6.17±0.06	6.36±0.08	6.35±0.04	6.56±0.07
Ar <sup>3+</sup>	3.89±0.22	4.23±0.23	4.01±0.18	4.24±0.19	4.78±0.06	5.04±0.08
Fe <sup>+</sup>	4.62:	4.78:	4.51:	4.62:	4.04:	4.13:
Fe <sup>++</sup>	5.07±0.04	5.41±0.08	5.23±0.10	5.47±0.12	5.24±0.06	5.50±0.09

<sup>a</sup> In units of  $12+\log(X^m/H^+)$ .**Table 7.** C<sup>++</sup>/H<sup>+</sup> abundance ratio from C II lines

Mult.	$\lambda_0$	$I(\lambda)/I(H\beta)$ ( $\times 10^{-2}$ )	M16		M20		NGC 3603			
			C <sup>++</sup> /H <sup>+</sup> ( $\times 10^{-5}$ )		C <sup>++</sup> /H <sup>+</sup> ( $\times 10^{-5}$ )		$I(\lambda)/I(H\beta)$ ( $\times 10^{-2}$ )	C <sup>++</sup> /H <sup>+</sup> ( $\times 10^{-5}$ )		
			A	B	A	B		A	B	
2	6578.05	0.310±0.019	365±22	60±4	0.356±0.021	414±25	68±4	0.250±0.023	264±24	47±4
3	7231.12	0.096±0.007	2533±177	36±3	0.075±0.007	1971±177	28±3	0.086±0.006	2300±161	33±2
	7236.19	0.178±0.012	2660±200	38±2	0.126±0.009	1884±132	27±2	0.179±0.011	2705±162	38±2
	Sum		2614±132	37±1		1915±106	27±1		2558±115	36±1
4	3918.98	0.138±0.018	2840±369	900±117	0.094±0.019	1885±377	595±119	—	—	—
	3920.68	0.162±0.019	1660±199	525±63	0.141±0.020	1420±199	450±63	—	—	—
	Sum		2060±175	650±55		1575±176	500±56	—	—	—
6	4267.26	0.272±0.019	25±2	<b>25±2</b>	0.170±0.020	15±2	<b>15±2</b>	0.325±0.059	31±6	<b>30±5</b>
17.02	9903.46	0.037±0.005 <sup>a</sup>	13±2	—	0.066:	24:	—	0.111±0.010 <sup>b</sup>	43±4	—
17.04	6461.95	0.032±0.012	28±10	—	0.043±0.011 <sup>c</sup>	38±10	—	—	—	—
Adopted			25±2		15±2		30±5			

<sup>a</sup> Affected by atmospheric absorption bands.<sup>b</sup> Blend with an unidentified line.<sup>c</sup> Affected by internal reflections or charge transfer in the CCD.

We have measured several lines of multiplet 1 of O II. As it has been pointed out by Tsamis et al. (2003) and Ruiz et al. (2003), the upper levels of the transitions of multiplet 1 of O II are not in LTE for densities  $n_e < 10000 \text{ cm}^{-3}$ , and the abundances derived from each individual line could differ by factors as large as 4. We have applied the NLTE corrections estimated by Peimbert, Peimbert & Ruiz (2005) to our data and the abundances obtained from the individual lines are in good agreement and also agree with the abundance derived using the sum of all the lines of the multiplet, which is not affected by NLTE effects. On the other hand, Tsamis et al. (2003) pointed out that, in the presence of absorption line features in the multiplet 1 spectral range, the emission lines could be attenuated. This effect can be very important in extragalactic objects, and it can only be corrected if the stars are resolved, or if synthetic spectra are available. In our case, our high resolution spectra shows, when compared with the spectrum of HD164492 (kindly provided by S. Simón-Díaz), the main ionizing source of M20,

that the continuum does not affect the measurement of multiplet 1 O II emission line fluxes, in spite of the large fraction of dust-scattered light of the nebular continuum (see § 9.1.1). Indeed, the situation may be quite different in the case of low spectral resolution observations, as was the case of Tsamis et al. (2003) for 30 Dor and LMC N11B. The O<sup>++</sup>/H<sup>+</sup> ratios for the three nebulae are presented in Table 9.

## 6 TOTAL ABUNDANCES

We have adopted a set of ionisation correction factors (ICF) to correct for the unseen ionisation stages and then derive the total gaseous abundances of the chemical elements we have studied. We have adopted essentially the ICF scheme used by García-Rojas et al. (2005) for all the elements, but we will discuss some special cases.

The absence of He II lines in our spectra indi-

**Table 8.** O<sup>+</sup>/H<sup>+</sup> ratio from O I permitted lines<sup>a</sup>

Mult.	$\lambda_0$	$I(\lambda)/I(\text{H}\beta)$ ( $\times 10^{-2}$ )	M16		$I(\lambda)/I(\text{H}\beta)$ ( $\times 10^{-2}$ )	M20		$I(\lambda)/I(\text{H}\beta)$ ( $\times 10^{-2}$ )	NGC 3603	
			O <sup>+</sup> /H <sup>+</sup> ( $\times 10^{-5}$ )			O <sup>+</sup> /H <sup>+</sup> ( $\times 10^{-5}$ )			O <sup>+</sup> /H <sup>+</sup> ( $\times 10^{-5}$ )	
			A	B		A	B		A	B
1	7771.94	0.026±0.006 <sup>b</sup>	26±6/34±8	—	0.036±0.006	36±6/47±8	—	—	—	—
4	8446.48	0.482±0.034	1849±129/ 2717±190	413±29/ 546±38	0.362±0.018	1383±69/ 2052±103	311±16/ 412±21	0.196±0.014	728±51/ 1165±82	171±12/ 2325±163
Adopted			30±7		42±7			—		

<sup>a</sup> Recombination coefficients by Pequignot, Petitjean & Boisson (1991)/Escalante & Victor (1992).

<sup>b</sup> Blended with telluric emission lines.

**Table 9.** O<sup>++</sup>/H<sup>+</sup> ratio from O II permitted lines<sup>a</sup>

Mult.	$\lambda_0$	$I(\lambda)/I(\text{H}\beta)$ ( $\times 10^{-2}$ )	M16		$I(\lambda)/I(\text{H}\beta)$ ( $\times 10^{-2}$ )	M20		$I(\lambda)/I(\text{H}\beta)$ ( $\times 10^{-2}$ )	NGC 3603	
			O <sup>++</sup> /H <sup>+</sup> ( $\times 10^{-5}$ )			O <sup>++</sup> /H <sup>+</sup> ( $\times 10^{-5}$ )			O <sup>++</sup> /H <sup>+</sup> ( $\times 10^{-5}$ )	
			A	B		A	B		A	B
1 <sup>b</sup>	4638.85	0.040±0.010	37±9/24±6	35±9/23±6	—	—	—	0.057:	52:/43:	50:/41:
	4641.81	0.034±0.010	13±3/15±4	13±3/14±4	0.030±0.015	12±6/14±7	11±6/13±7	0.131±0.033	49±12/51±13	47±12/49±12
	4649.14	0.056±0.011	12±2/20±4	11±2/19±4	0.036±0.018	8±4/20±10	7±4/19±10	0.172±0.034	36±7/42±8	35±7/41±8
	4650.84	0.050±0.011	49±11/28±6	47±11/27±6	0.030±0.015	17±9/8±4	16±8/7±4	0.086±0.029	84±28/65±22	81±27/63±21
	4661.64	0.038±0.010	31±8/20±5	30±8/19±5	0.018±0.014	15±12/8±6	14±11/8±6	0.111±0.031	90±25/74±21	87±24/72±20
	4676.24	—	—	—	—	—	—	0.040:	42:/44:	41:/43:
	4696.36	—	—	—	—	—	—	0.037 <sup>c</sup> :	381:/325:	368:/304:
	Sum	—	21±2	20±2	—	11±5	10±5	—	53±6	51±6
2	4349.43	—	—	—	—	—	—	0.148:	32:	31:
Adopted			20±2		10±5			51±6		

<sup>a</sup> Except in the case of M20, only lines with intensity uncertainties lower than 40 % have been considered (see text)

<sup>b</sup> Not corrected from NLTE effects/Corrected from NLTE effects (see text).

<sup>c</sup> Probably is a misidentification

cates that He<sup>++</sup>/H<sup>+</sup> is negligible. However, the total helium abundance has to be corrected for the presence of neutral helium. Based on the ICF(He<sup>0</sup>) given by Peimbert, Torres-Peimbert & Ruiz (1992) and with our data, the ICF(He<sup>0</sup>) amounts to 1.18±0.05, 1.16±0.05 and 1.007±0.002 for  $t^2 > 0.00$ , for M16, M20 and NGC 3603, respectively.

For all the nebulae, we have derived the O/H ratio from CELs, from the combination of O<sup>++</sup>/H<sup>+</sup> ratio from RLs and O<sup>+</sup>/H<sup>+</sup> ratio from CELs and the assumed  $t^2$  (for M16 and NGC 3603) and, for the first time for M20, from pure recombination lines of O<sup>+</sup> and O<sup>++</sup>. In Table 10 we show the total abundances obtained in our nebulae for  $t^2 = 0.00$  and  $t^2 > 0.00$ .

For neon, we have used the ICF proposed by Peimbert & Costero (1969):

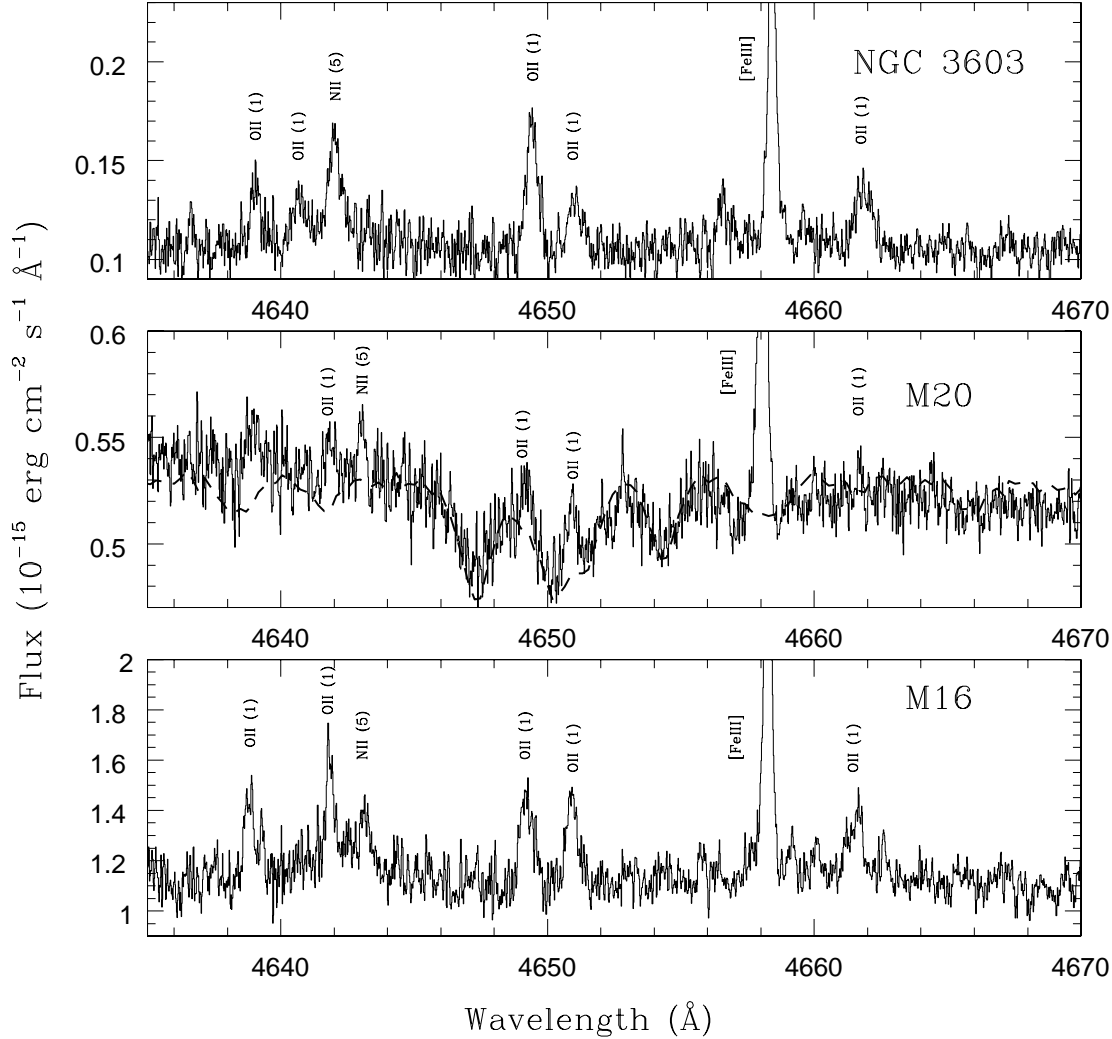
$$\frac{N(\text{Ne})}{N(\text{H})} = \left( \frac{N(\text{O}^+) + N(\text{O}^{++})}{N(\text{O}^{++})} \right) \frac{N(\text{Ne}^{++})}{N(\text{H}^+)}. \quad (1)$$

Nevertheless this ICF underestimates the Ne/H abundance for nebulae of low degree of ionisation because a considerable fraction of Ne<sup>+</sup> coexists with O<sup>++</sup> (see Torres-Peimbert & Peimbert 1977; Peimbert, Torres-Peimbert & Ruiz 1992). This is the case for M16 and M20. Based on the O<sup>+</sup>/O ratio, the data and the prescriptions by Torres-Peimbert & Peimbert (1977), we estimate that the ICF(Ne)<sup>+</sup> should be about 0.14 ± 0.1 dex for M16 and 0.42 ± 0.1 dex for M20 higher than those provided by equation (1) for  $t^2 = 0.00$ . From these ICF(Ne)<sup>+</sup> we derive an Ne/O ratio of about 0.2 for both regions. This ratio is in excellent agreement with the Ne/O ratios

derived for M17 by Peimbert, Torres-Peimbert & Ruiz (1992), and by us for NGC 3603, where most of the O and Ne are twice ionized and the ICF(Ne) is very small. Given the high ionisation degree for NGC 3603, equation 1 is a good approximation to the fraction of Ne<sup>+</sup> in this nebula.

We have measured lines of two ionisation stages of chlorine in M16 and M20: Cl<sup>+</sup> and Cl<sup>++</sup>. The Cl abundance has been assumed to be equal to the sum of these ionic abundances without taking into account the Cl<sup>3+</sup> fraction. This assumption seems reasonable taking into account the small Cl<sup>3+</sup>/Cl<sup>++</sup> ratio found for M17 (~0.03, see Esteban et al. 1999a), for the Orion nebula (~0.04, see Esteban et al. 2004), for NGC 3576 (~0.02, see García-Rojas et al. 2004), and for NGC 3603 (~0.06, this work) and the lower ionisation degree of M16 and M20 with respect to those nebulae. In NGC 3603 we have detected three ionisation stages of chlorine and the total abundance includes the sum of the Cl<sup>+</sup>, Cl<sup>++</sup> and Cl<sup>3+</sup> abundances. Using the ICF by Peimbert & Torres-Peimbert (1977) to correct for the presence of Cl<sup>3+</sup>, we have obtained abundances 0.13 and 0.07 dex higher for M16 and M20, and 0.02 dex lower for NGC 3603, showing that this ICF scheme is a good approximation when [Cl IV] lines are not detected in the spectrum of H II regions with high degree of ionisation, however, it overestimates the contribution of Cl<sup>3+</sup> for the low ionisation regime.

We have measured lines of two stages of ionisation of iron: Fe<sup>+</sup> and Fe<sup>++</sup>. As we have commented in § 5.2, the Fe<sup>+</sup> abundance is somewhat uncertain, so we have used the ICF scheme by Rodríguez & Rubin (2005) (based on pho-



**Figure 2.** Section of the echelle spectra showing the lines of multiplet 1 of O II (observed fluxes) for the three H II regions. In the case of M20, we have superimposed the spectrum of HD164492 (dashed line), which is normalized to the continuum flux in the zone of O II 4649 and 4650 Å lines. It can be seen that the fluxes of multiplet 1 emission lines may be measured simply integrating the line flux between the closest points of the local adjacent continuum, and that these lines are not seriously attenuated by the dust-scattered light (see text).

toionization models) to derive the total Fe/H ratio from the  $\text{Fe}^{++}$  abundance, which is given by:

$$\frac{N(\text{Fe})}{N(\text{H})} = 0.9 \left[ \frac{N(\text{O}^+)}{N(\text{O}^{++})} \right]^{0.08} \times \frac{N(\text{Fe})^{++}}{N(\text{O})^+} \times \frac{N(\text{O})}{N(\text{H})}, \quad (2)$$

In the case of high ionisation degree nebulae, Rodríguez & Rubin (2005) used a further relation based on an observational fit, which is given by:

$$\frac{N(\text{Fe})}{N(\text{H})} = 1.1 \left[ \frac{N(\text{O}^+)}{N(\text{O}^{++})} \right]^{0.58} \times \frac{N(\text{Fe})^{++}}{N(\text{O})^+} \times \frac{N(\text{O})}{N(\text{H})}; \quad (3)$$

This last relation has been applied to obtain the Fe/H ratio of NGC 3603. The discrepancy observed between the Fe abundance obtained making use of equation (2) or (3) for high ionisation degree nebulae (e.g. see NGC 3603 Fe

abundance on Table 10) has been extensively discussed by Rodríguez & Rubin (2005). From Table 10 it is clear that the sum of  $\text{Fe}^+$  and  $\text{Fe}^{++}$  abundances for M16 and M20 respectively are almost coincident with those derived using an ICF. In fact, for these regions, it is not expected a large contribution of  $\text{Fe}^{3+}$  to the total abundance, due to their low ionisation degree. This is not true for objects with high ionisation degree as NGC 3603, for which the fraction of  $\text{Fe}^{3+}$  is expected to be large; this is reflected in the large difference between the two values of Fe/H ratio given in Table 10. It is obvious that the sum of  $\text{Fe}^+$  and  $\text{Fe}^{++}$  abundances is not applicable for this object, we must rely on the results obtained assuming an ICF.



**Table 10.** Total Gaseous Abundances.

Element	M16		M20		NGC 3603	
	$t^2=0.000$	$t^2=0.039\pm 0.006$	$t^2=0.000$	$t^2=0.029\pm 0.007$	$t^2=0.000$	$t^2=0.040\pm 0.008$
He	11.01±0.02	10.97±0.02	10.95±0.06	10.92±0.06	10.99±0.01	10.99±0.01
C	8.76±0.06	8.76±0.06	8.69±0.08	8.69±0.08	8.51±0.07	8.51±0.07
N	7.84±0.06	8.07±0.12	7.67±0.05	7.83±0.07	7.62±0.13	7.89±0.14
O	8.56±0.07	8.78±0.07	8.53±0.06	8.67±0.07	8.46±0.05	8.71±0.07
O <sup>a</sup>	8.81±0.07	8.81±0.07	8.71±0.07	8.71±0.07	8.72±0.05	8.72±0.05
Ne	7.86±0.15	8.08±0.17	7.83±0.16	7.97±0.18	7.76±0.08	8.03±0.11
S	6.96±0.05	7.29±0.08	6.88±0.05	7.12±0.09	7.03±0.05	7.36±0.08
Cl <sup>b</sup>	5.23±0.04	5.49±0.07	5.19±0.05	5.37±0.06	5.09±0.05	5.33±0.07
Ar	6.70±0.07	6.84±0.08	6.65±0.06	6.70±0.11	6.37±0.15	6.58±0.17
Fe <sup>c</sup>	5.17±0.11	5.53±0.13	5.31±0.13	5.56±0.15	6.14±0.16/5.74±0.10	6.53±0.19/6.05±0.10
Fe <sup>d</sup>	5.20±0.06	5.51±0.07	5.31±0.09	5.52±0.10	5.27±0.06	5.52±0.09

<sup>a</sup> For M20, O<sup>+</sup>/H<sup>+</sup> and O<sup>++</sup>/H<sup>+</sup> from RLs. For M16 and NGC 3603, O<sup>++</sup>/H<sup>+</sup> from RLs and O<sup>+</sup>/H<sup>+</sup> from CELs and  $t^2$ .

<sup>b</sup> For NGC 3603, from Cl<sup>+</sup>/H<sup>+</sup>+Cl<sup>++</sup>/H<sup>+</sup>+Cl<sup>3+</sup>/H<sup>+</sup>. For M16 and M20, from Cl<sup>+</sup>/H<sup>+</sup>+Cl<sup>++</sup>/H<sup>+</sup>.

<sup>c</sup> ICF from equation 2 for M16 and M20; ICF from equation2/equation 3 for NGC 3603.

<sup>d</sup> Fe/H = Fe<sup>+</sup>/H<sup>+</sup> + Fe<sup>++</sup>/H<sup>+</sup>.

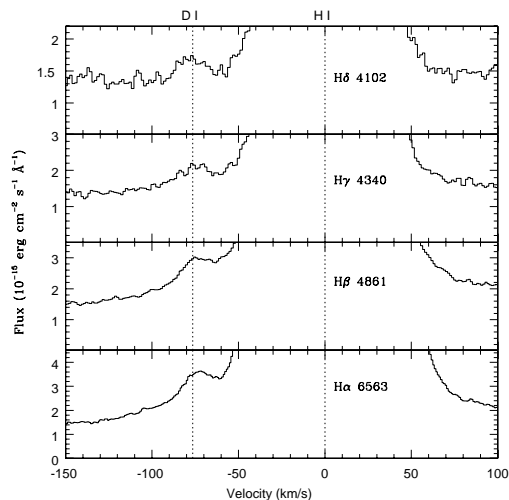
**Table 11.** Deuterium Balmer line properties in M16 and M20.

Line	D I Isotopic shift (km s <sup>-1</sup> )	FWHM D I (km s <sup>-1</sup> )	FWHM H I (km s <sup>-1</sup> )	D I/H I ratio (×10 <sup>-4</sup> )
M16				
α	-75.4	<10:	24	1.0 ± 0.3
β	-76.5	<10:	24	3.2 ± 0.9
γ	-76.7	<10:	24	6.4 ± 2.4
δ	-77.5	<10:	24	8.2:
M20				
α	-92.7	<10:	25	2.0 ± 0.4
β	-90.7	<10:	20	3.9 ± 1.5
γ	-89.1	<10:	21	4.7:

## 7 DEUTERIUM BALMER LINES IN M16 AND M20

Hébrard et al. (2000) reported the detection of deuterium Balmer lines in the spectrum of M16 and M20. These authors detected from Dα to Dγ in M16 and only Dα in M20. We have detected several deuterium Balmer lines in M16 –from Dα to Dδ– and in M20 –from Dα to Dγ–; these lines appear as very weak emission features in the blue wings of the corresponding H I Balmer lines (see figures 3 and 4). The apparent shifts in radial velocity of these lines with respect to the hydrogen ones are -76.5 km s<sup>-1</sup> for M16 and -90.8 km s<sup>-1</sup> for M20, which are roughly consistent with the expected isotopic shift of deuterium, -81.6 km s<sup>-1</sup>.

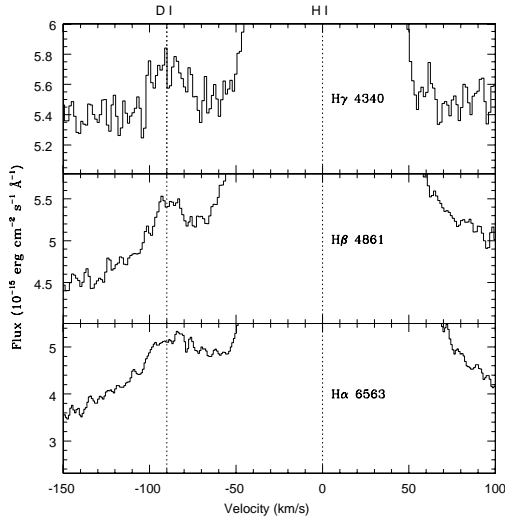
We have excluded the possibility that these weak features are high velocity components of hydrogen following the same criteria as García-Rojas et al. (2005) for the case of S 311. The first criterion is the absence of similar high-velocity components associated to bright lines of other ions. The second is that the full width at half maximum (FWHM) of the deuterium lines is narrower than 10 km s<sup>-1</sup> in all cases, much narrower than the H I Balmer lines (see Figures 3 and 4), which have FWHM between 20 and 25 km



**Figure 3.** Wings of Hα to Hδ in M16. The lines are centred at 0 km s<sup>-1</sup> velocity. The dotted line of the left correspond to the average wavelength adopted for the D I lines.

s<sup>-1</sup>. This fact supports the idea that deuterium lines arise from much colder material, probably from the photon dominated region (Hébrard et al. 2000).

In order to strengthen the conclusions about the nature of the emission of D I Balmer lines we have compared the Balmer decrements of the hydrogen and deuterium lines observed in our spectra with the standard fluorescence models by O’Dell, Ferland & Henney (2001, see their Figure 13) for the Orion nebula, finding that our observations follow closely this model, indicating that fluorescence should be the main excitation mechanism of the D I lines observed in M16 and M20 (see Table 11).



**Figure 4.** Same as figure 4 for M20.

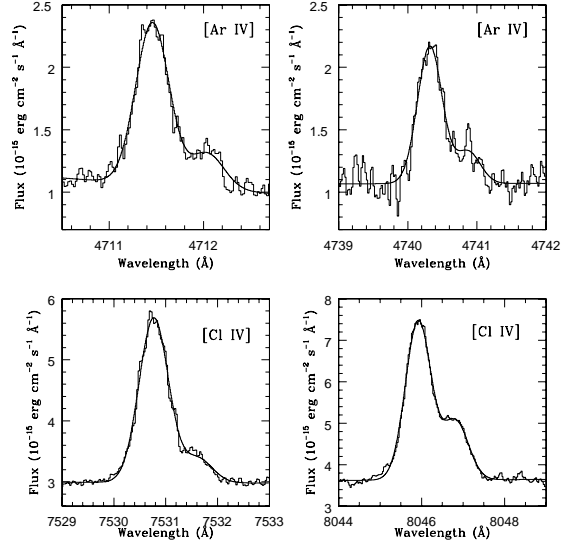
## 8 HIGH-VELOCITY COMPONENTS IN NGC 3603

We have detected weak emission features in the red wing of the highest ionisation potential lines in the spectrum of NGC 3603: those of [Ar IV]  $-40.74$  eV $^-$  and [Cl IV]  $-39.61$  eV $^-$  (see Figure 5). These features are redshifted  $\sim 36$  km s $^{-1}$  (argon), and  $\sim 33$  km s $^{-1}$  (chlorine) with respect to the [Ar IV] and [Cl IV] lines. The FWHM of these presumed high-velocity components is similar ( $\sim 18$  km s $^{-1}$ ) to that of the main component. The redshifted component is also detectable in the line profiles of other lines (see Figure 6), but it is much less evident, with a contrast that decreases as the ionisation potential of the ion that produces the line decreases. This indicates that the redshifted component is composed by a gas with a higher ionisation degree than the main component. An additional fainter and blue-shifted component seems to be present in the lines of the low ionisation potential ions, as [N II] and [S II].

Clayton (1990) obtained high spectral resolution [O III] profiles at different zones of NGC 3603 finding a clear red component in the [O III] 5007 Å line along most of the spatial extension of the nebula. At or very near our slit position, he detects that this second component shows a velocity shift between 30 and 40 km s $^{-1}$  with respect to the main one, values consistent with our reported velocity separations. The gas motions in NGC 3603 are rather complex and can be interpreted as the product of different expanding structures with velocities up to 100 km s $^{-1}$ .

## 9 DISCUSSION

In order to improve the clarity of this paper, we have divided the discussion in different subsections, one devoted to M16 and M20, and another one devoted to the discussion of NGC 3603, whose peculiarities and its status as a Galactic example of giant H II region make it a specially interesting object.



**Figure 5.** Redshifted components in the wings of [Ar IV] and [Cl IV] lines in NGC 3603.

**Table 12.** M20 Continuum determinations<sup>a</sup>

$\lambda(\text{\AA})$	$\log(j(\lambda)/j(\text{H}\beta))$		
	Atomic	Observed	Scattered light
3640	-2.179	$-1.528 \pm 0.007$	$-1.638 \pm 0.008$
3670	-3.094	$-1.634 \pm 0.004$	$-1.649 \pm 0.004$
4110	-3.246	$-1.733 \pm 0.003$	$-1.746 \pm 0.003$
4350	-3.281	$-1.818 \pm 0.004$	$-1.833 \pm 0.004$
4850	-3.316	$-2.007 \pm 0.004$	$-2.029 \pm 0.004$
6570	-3.346	$-2.370 \pm 0.006$	$-2.419 \pm 0.008$
8175	-3.332	$-2.674 \pm 0.002$	$-2.783 \pm 0.003$
8260	-4.001	$-2.678 \pm 0.008$	$-2.957 \pm 0.015$

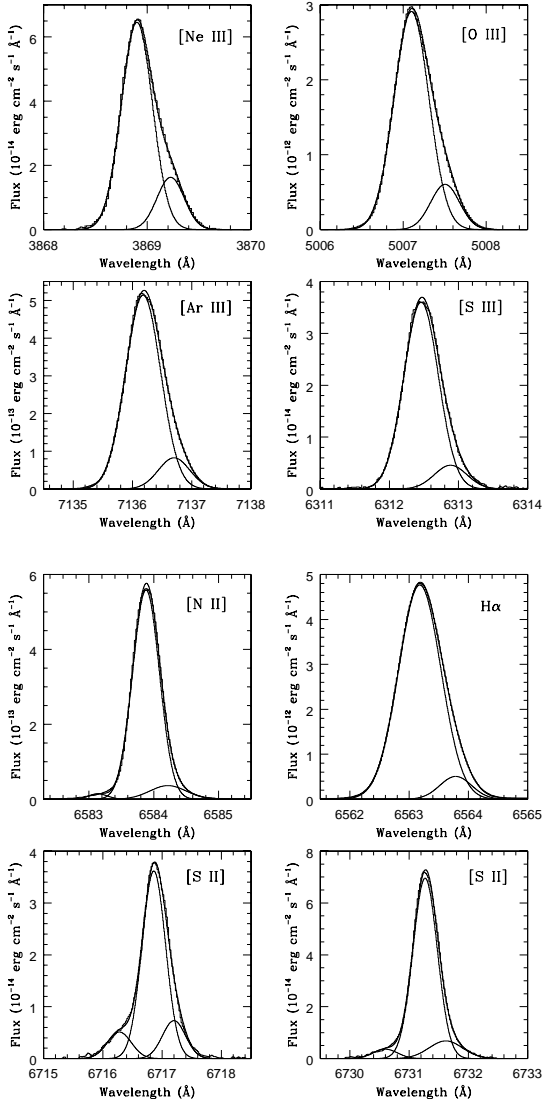
<sup>a</sup> in units of ( $\text{\AA}^{-1}$ )

### 9.1 M20 and M16

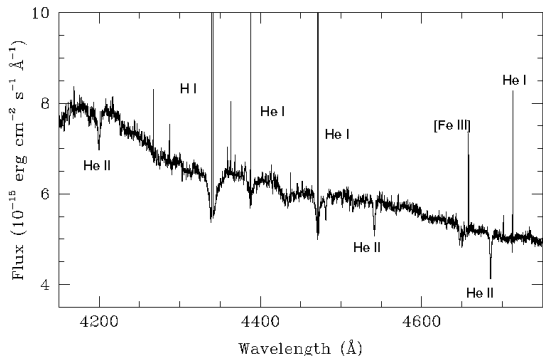
#### 9.1.1 M20 Continuum determinations

In the case of M20, our slit position is located in a bright zone very near its ionising star HD164492 ( $17''$  north and  $10''$  east). This bright zone is just at the border of one of the dust lanes that crosses the nebula. Therefore, it is not strange that the stellar scattered light contribution in this spectra is specially high. This can be noted in the absorption features present in Figure 2 and in Figure 7, where we detect the stellar He II absorptions at  $\lambda\lambda 4200, 4542$  and  $4686$  Å as well as absorption in the H I Balmer lines.

In Table 12 we show the observed and the expected nebular continua as well as the estimated scattered light contribution for different wavelengths. The nebular atomic continuum is the sum of the continua produced by H I and He I and it has been derived for the physical conditions and the He/H ratio computed for M20. From the table, it is evident that the scattered light is the main contribution to the observed continuum. As expected for normal dust properties, we have also found that the amount of stellar scattered light increases systematically towards bluer wavelengths (see Table 12). Using the observed equivalent widths of the He II absorption



**Figure 6.** Components in the wings of [Ne III], [O III], [Ar III], [S III], [N II], [S II] lines and H $\alpha$  in NGC 3603. Ionisation Potential of the ions that produce the lines decreases from top to bottom and from left to right.



**Figure 7.** Section of the echelle spectrum showing the absorption  $\lambda\lambda 4200$  Å,  $4542$  Å and  $4686$  Å He<sup>+</sup> lines.

lines and those detected in the spectrum of HD164492<sup>3</sup> it is possible to estimate the fraction of dust scattered light, using the expression used by Sánchez & Peimbert (1991):

$$\frac{i_d(\lambda)}{i} = \frac{\sum EW(M20)}{\sum EW(HD164492)}, \quad (4)$$

where  $i_d(\lambda)/i$  is the fraction of dust scattered light in M20 with respect to the total emission of HD164492 at a given wavelength range. From this expression we have obtained  $i_d/i = 0.54 \pm 0.09$ ; on the other hand, the fraction of the continuum scattered light with respect to the observed continuum in the 4200 to 4850 Å range in M20 amounts to  $0.96 \pm 0.01$ . O'Dell, Hubbard & Peimbert (1966) reported that the effective dust-to-gas ratio is 5 times higher in M20 than in other gaseous nebulae or the interstellar medium; also, Robledo-Rella (2002) reported that the nebular continuum of M20 is strongly dominated by dust-scattered light. These results agree with the high fraction of dust scattered light observed in the continuum of M20. This high fraction of dust scattered light could be due to the closeness of our slit position to HD164492, moreover, other nearby stars could be contributing to the observed continuum.

### 9.1.2 Comparison with other abundance determinations

As we have stated in section 5.2, we have derived our ionic abundances from CELs making use of all the individual lines (which are not blended with other lines) of each ion observed. All the individual ionic abundances are consistent, within the errors, with the adopted weighted mean, except for the case of S<sup>+</sup>, for which we have obtained larger differences because we have used  $T_e(\text{low})$  instead of  $T_e([\text{S II}])$  to derive S<sup>+</sup> abundances. In fact, the largest differences are between abundances derived from  $\lambda\lambda 6717, 6731$  Å and from  $\lambda\lambda 10329, 10336$  and  $10371$ Å, (over 0.15 dex in the case of M16), but these last lines have less weight in the final adopted value.

Previous abundance determinations in M20 and M16 are those of Hawley (1978) and Rodríguez (1998, 1999b). All of them are based on the analysis of CELs. Although the slit positions studied in these works are different, we have compared their results with ours. For the sake of consistency we have re-computed the abundances given by those authors using the same set of atomic data and ICF scheme than in this paper. Moreover, taking into account that the previous works obtained abundances in several slit positions across the nebula, we have taken average values for the comparison.

In general there is a good agreement between our O, N and S abundances obtained from CELs and those obtained by Hawley (1978) within the errors. Departures from our values are smaller than 0.1 dex for N, and the O abundance is almost coincident in the case of M20 and 0.09 dex lower in the case of M16. Taking into account that Hawley highlighted the difficulties in the measurement of some lines

<sup>3</sup> This spectrum was obtained with the Intermediate Dispersion Spectrograph (IDS) attached to the INT 2.5m Telescope of the Roque de los Muchachos observatory in La Palma, Spain. The results used here were kindly provided by Sergio Simón-Díaz (private communication)

(those of [N II] and [S III]) in his spectra, the agreement with our results is remarkable.

We have followed the same methodology to compare with the results of Rodríguez (1998, 1999b). For M20, N and S show differences of 0.06 dex and 0.09 dex respectively, but the O abundance shows a larger discrepancy (0.21 dex), mainly due to differences in the  $O^+/H^+$  ratio. This difference can be explained because Rodríguez determined the  $O^+/H^+$  ratio from the [O II] 7320+7330 Å lines, which were severely affected by sky telluric lines (Rodríguez 1998). For M16 there is a good agreement between our results and Rodríguez ones, specially for N and S abundances, which are almost coincident with our values. The discrepancy in the O abundance is, in this case, of 0.11 dex, probably due to the same reason pointed out above.

## 9.2 NGC 3603

As it was commented in the introduction, NGC 3603 is the only Galactic giant H II region that can be observed in the visual. Melnick, Tapia & Terlevich (1989) derived an O abundance for NGC 3603 of  $12 + \log(O/H) = 8.39 \pm 0.41$ . In spite of its extremely large uncertainty, this value is in good agreement with our derived O/H abundance ratio from CELs. On the other hand, Tapia et al. (2001) published the most complete set of abundances in the literature for NGC 3603 until now; their O/H ratio is only 0.06 dex higher than ours, and the large differences in the other abundance ratios are probably due to their large line intensity uncertainties and the different set of ICFs used. We have found a similar behaviour comparing our abundances based on CELs with those of Girardi et al. (1997).

For NGC 3603, we have available O, N, Ne and S abundance determinations based on far-infrared fine-structure line observations (Simpson et al. 1995). Since the emissivity of these lines is essentially independent of the nebular thermal structure –due to their low excitation energies, it is interesting to compare abundances derived from these lines with those derived from recombination lines or from optical CELs assuming a  $t^2$ . In principle, assuming the temperature fluctuations paradigm, and that there are no large density fluctuations, all these determinations might be similar. In Table 13 we compare our derived total and ionic abundances for NGC 3603 (this work) with those obtained by Simpson et al. (1995). In spite of the high uncertainty of the abundances derived by Simpson et al. (1995) (due to the uncertainty in the radio flux and aperture effects), values derived from IR CELs and those derived from optical CELs assuming a  $t^2 > 0$  are similar, a fact that seems to support the presence of temperature fluctuations in the nebula. However, there are other examples where this is not clear; from a similar comparison between optical data and Simpson’s IR data, other results have been found: NGC 3576 (Tsamis et al. 2003; García-Rojas et al. 2005) and Orion nebula (Tsamis et al. 2003; Esteban et al. 2004) show IR abundances which are intermediate between  $t^2=0.00$  and  $t^2 > 0$ , and M17 (Tsamis et al. 2003; Esteban et al. 1999a) and 30 Doradus (Peimbert 2003; Tsamis et al. 2003) show IR abundances which are rather similar to those derived from optical CELs and  $t^2=0.00$ . Moreover, the comparison of our slit optical spectroscopy and the IR data of Simpson et al. (1995) shows a further complication, at least for the ionic

abundances. The aperture used in both kinds of observations cover a very different area of the nebula, which is much larger in the IR spectroscopy. Changes in the mean ionisation degree of the area covered in optical and IR observations may produce natural differences in the ionic abundances not related to the presence or absence of a temperature structure. In contrast, this effect should not affect the total abundances. In this sense, we think important to clarify the conclusion drawn by Tsamis et al. (2003) about this issue. Those authors make the comparison between the  $O^{++}/H^+$  abundances derived from optical and IR CELs for a sample of H II regions, and conclude that temperature fluctuations might be ruled out as the cause of the discrepancy found between  $O^{++}/H^+$  abundances derived from optical RL and CELs. From our apparently positive results for NGC 3603 and taking into account the aperture consideration, that conclusion seems to be far from conclusive. It is clear that further IR and optical observations taken in the same zones and with similar apertures are needed to settle definitively this problem.

## 10 CONCLUSIONS

We present deep echelle spectroscopy in the 3100-10400 Å range of bright zones of the Galactic H II regions M16, M20 and NGC 3603. We have measured the intensity of about 250 lines per object. This is the most complete set of emission lines ever obtained for these three objects.

We have derived the physical conditions of each nebula making use of several line intensities and continuum ratios. The chemical abundances have been derived using the intensity of collisionally excited lines (CELs) for a large number of ions of different elements. We have determined, for the first time in the three objects, the  $C^{++}$  and  $O^{++}$  abundances from recombination lines (RLs) and, finally we have also determined the abundance of  $O^+$  from RLs for the first time in M20.

We have obtained consistent estimations of the temperature fluctuations parameter,  $t^2$ , applying different methods: by comparing the  $O^+$  (when available) and  $O^{++}$  ionic abundances derived from RLs to those derived from CELs; by applying a chi-squared method which minimizes the dispersion of  $He^+/H^+$  ratios from individual lines; and by comparing the electron temperatures derived from CELs to those derived from Balmer and Paschen continua. The adopted average value of  $t^2$  has been used to correct the ionic abundances derived from CELs.

We report the detection of several deuterium Balmer lines in the spectra of M16 and M20. The properties of these lines indicate that fluorescence is their most probable excitation mechanism.

We have compared the results obtained for optical CELs in NGC 3603 with those obtained from far-infrared fine-structure CELs finding an apparent agreement, in spite of the high uncertainties of the abundances derived from far IR data, if the temperature fluctuations paradigm is assumed. However, IR and optical spectrophotometry covering the same volume of the nebula is necessary to make a reliable and conclusive comparison between optical and IR CEL abundances.

**Table 13.** Comparison of optical and IR abundances for NGC 3603<sup>a</sup>

Element/Ion	Opt CELs <sup>b</sup> ( $t^2 = 0.00$ )	Opt CELs <sup>b</sup> ( $t^2 > 0.00$ )	IR CELs <sup>c</sup>
O	8.46 ± 0.05	8.72 ± 0.05	8.79 ± 0.09
N	7.62 ± 0.13	7.89 ± 0.14	7.96 ± 0.09
S	7.03 ± 0.05	7.36 ± 0.08	7.12 ± 0.09
Ne	7.76 ± 0.08	8.03 ± 0.11	8.08
O <sup>++</sup>	8.42 ± 0.05	8.68 ± 0.08	8.61 ± 0.09
S <sup>++</sup>	6.83 ± 0.04	7.11 ± 0.09	6.90 ± 0.12
Ne <sup>++</sup>	7.72 ± 0.05	8.00 ± 0.08	7.85 ± 0.09

<sup>a</sup> In logarithmic units.<sup>b</sup> This work.<sup>c</sup> Simpson et al. (1995).

## ACKNOWLEDGMENTS

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