CHEMICAL COMPOSITION OF TWO H II REGIONS IN NGC 6822 BASED ON VLT SPECTROSCOPY

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ABSTRACT

We present long-slit spectrophotometry of regions V and X of the Local Group irregular galaxy NGC 6822. The data consist of VLT FORS observations in the 3450–7500 Å range. We have obtained electron temperatures and densities using different line intensity ratios. We have derived the He, C, and O abundances relative to H based on recombination lines; the abundance ratios among these elements are almost independent of the temperature structure of the nebulae. We have also determined the N, O, Ne, S, Cl, and Ar abundances based on collisionally excited lines; the ratios of these abundances relative to that of H depend strongly on the temperature structure of the nebulae. The chemical composition of NGC 6822 V is compared with those of the Sun, the Orion Nebula, NGC 346 in the SMC, and 30 Doradus in the LMC. The value of O/H derived from recombination lines is in good agreement with that derived by Venn and coworkers from two A-type supergiants in NGC 6822.

Subject headings: galaxies: abundances — galaxies: individual (NGC 6822) — H II regions

1. INTRODUCTION

The main aim of this paper is to make a new determination of the chemical abundances of the two brightest H II regions in NGC 6822, regions V and X (Hubble 1925). We include the following improvements over previous determinations: the consideration of the temperature inhomogeneities that affect the helium and heavy-element abundance determinations, the derivation of the O and C abundances from recombination line intensities, the consideration of the collisional excitation of the triplet He i lines from the 2 3S level by determining the helium abundance from many line intensity ratios, and the study of the 2 3S level optical depth effects on the intensity of the triplet lines by observing a large number of singlet and triplet lines of He i.

We are interested in three applications based on the abundance determinations: the determination of \( T^2 \), the comparison of the nebular abundances derived in this paper with the stellar abundances of supergiant stars in NGC 6822 derived elsewhere (Muschielok et al. 1999; Venn et al. 2001, 2004; Venn & Miller 2002), and providing accurate abundances for galactic chemical evolution models of this object (e.g., Carigi et al. 2005a).

NGC 6822 is an irregular galaxy member of the Local Group particularly suited for chemical evolution models because its star formation history is well known (Wyder 2001) and because it apparently has not been affected by tidal effects; therefore, its chemical composition may permit us to determine whether outflows to the intergalactic medium from nearby irregular galaxies depends on many factors, such as their total mass, the distribution in time and space of their star formation, and tidal effects (e.g., Legrand et al. 2001; Tenorio-Tagle et al. 2003; Martin 2003; Fragile et al. 2004 and references therein).

NGC 6822 apparently has not been affected by tidal effects from the main galaxies of the Local Group, the Milky Way and M31 (Sawa & Fujimoto 2005). NGC 6822 is located at 495 kpc from our Galaxy and is moving away from it at a radial velocity of 44 km s\(^{-1}\) (Trimble 2000). NGC 6822 is also located at 880 kpc from M31 and is separated from M31 by more than 90° in the sky (Trimble 2000).

In §§ 2 and 3 the observations and the reduction procedure are described. In § 4 temperatures and densities are derived from four and three different intensity ratios, respectively; also in this section, the mean square temperature fluctuation, \( T^2 \), is determined from the O ii/\([\text{O III}]\) line intensity ratios and from the difference between \( T(\text{He i}) \) and \( T([\text{O III}]+\text{O ii}) \). In § 5 we determine ionic abundances based on recombination lines that are almost independent of the temperature structure and also determine ionic abundances based on ratios of collisionally excited lines to recombination lines that do depend on the temperature structure of the nebula. In § 6 we determine the total abundances. In §§ 7 and 8 we present the discussion and the conclusions.

2. OBSERVATIONS

The observations were obtained with the Focal Reducer Low Dispersion Spectrograph 1 (FORS1) at the Very Large Telescope (VLT) Melipal Telescope in Chile. We used three grisms: GRIS 600B+12, GRIS 600R+14 with filter GG435, and GRIS 300V with filter GG375 (see Table 1).

The slit was oriented almost east-west (position angle 91°) to observe the brightest regions of NGC 6822 V and X simultaneously. The linear atmospheric dispersion corrector (LACD) used to keep the same observed region within the slit regardless of the airmass value. The slit length was set to 0.51 arcmin and the slit length was 41°. The aperture extractions were made for an area of 22″ × 0.51 arcmin for region V and an area of 24″ × 0.51 for region X, covering the brightest parts of both regions (see Fig. 1). The resolution for the emission lines observed with the blue grism is given by \( \Delta \lambda \approx \lambda/1300 \), with the red grism is given by \( \Delta \lambda \approx \lambda/1700 \), and with the low-resolution grism is given by \( \Delta \lambda \approx \lambda/700 \). The average seeing during the observations amounted to 0.8.

1 Based on observations collected at the European Southern Observatory, Chile, proposal ESO 69.C-0203(A).
The spectra were reduced using IRAF\(^2\) reduction packages, following the standard procedure of bias subtraction, aperture extraction, flat-fielding, wavelength calibration, and flux calibration. For flux calibration the standard stars LTT 2415, LTT 7389, LTT 7987, and EG 21 were used (Hamuy et al. 1992, 1994). The observed spectra are presented in Figures 2 and 3.

### 3. LINE INTENSITIES, REDDENING CORRECTION, AND RADIAL VELOCITIES

Line intensities were measured by integrating all the flux in the line between two given limits and over a local continuum estimated by eye. In the few cases of line blending, the line flux of each individual line was derived from a multiple Gaussian profile fit procedure. All these measurements were carried out with the \texttt{splot} task of the IRAF package.

The reddening coefficients, \(C(H_\beta/C_12)\), were determined by fitting the observed \(I(H_\beta)/I(H\text{ Balmer lines})\) ratios to the theoretical ones computed by Storey & Hummer (1995) for \(T_e = 10,000\) K and \(N_e = 100\) cm\(^{-3}\) (see below) and assuming the extinction law of Seaton (1979).

Table 2 presents the emission-line intensities of the NGC 6822 H\textsc{ii} regions. Columns (1) and (2) include the adopted laboratory wavelength, \(\lambda\), and the identification for each line, respectively. Columns (3) and (4) include the observed flux relative to \(H_\beta\), \(F(\lambda)\), and the flux corrected for reddening relative to \(H_\beta\), \(R(\lambda)\), respectively, for region V. Columns (5) and (6) include the same information as the previous two but for region X. To combine all the line intensities from the three different instrumental settings on the same scale, we multiplied the intensities in each setting by a correction factor obtained from the lines present in more than one setting. The errors were estimated by comparing all the measured H line intensities with those predicted by the computations of Storey & Hummer (1995) and by assuming that the signal-to-noise ratio (S/N) increases as the square root of the measured flux. These estimates are in agreement with the differences found when comparing the line fluxes observed in different exposures.

### 4. PHYSICAL CONDITIONS

#### 4.1. Temperatures and Densities

The temperatures and densities presented in Table 3 were derived from the line intensities presented in Table 2. The

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\(^2\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
determinations were carried out based on the temden IRAF subroutine; this subroutine models a five-, six-, or eight-level ion to derive these quantities.

To compute \( T([\text{O} \, \text{II}]) \), the contribution to the intensities of the \( 7320, 7330, 7331, \) and \( 7332 \) [O II] lines due to recombination was taken into account based on the following equation (see Liu et al. 2000):

\[
\frac{I_R(7319 + 7320 + 7331 + 7332)}{I(\text{H}\beta)} = 9.36 \left( \frac{T}{10^4} \right)^{0.44} \left( \frac{O^{++}}{H^+} \right).
\] (1)

Similarly, to compute \( T([\text{N} \, \text{II}]) \), the contribution to the intensity of the \( 5755 \) [N II] line due to recombination was taken into account based on the following equation (see Liu et al. 2000):

\[
\frac{I_R(5755)}{I(\text{H}\beta)} = 3.19 \left( \frac{T}{10^4} \right)^{0.30} \left( \frac{N^{++}}{H^+} \right).
\] (2)

### 4.2. Temperature Variations

To derive the ionic abundance ratios the average temperature, \( T_0 \), and the mean square temperature fluctuation, \( \tau^2 \), were used. These quantities are given by

\[
T_0(N_e, N_i) = \frac{\int T_e(r)N_e(r)N_i(r) \, dV}{\int N_e(r)N_i(r) \, dV},
\] (3)

\[
\tau^2 = \frac{\int (T_e - T_0)^2 N_eN_i \, dV}{T_0^2 \int N_eN_i \, dV},
\] (4)

respectively, where \( N_e \) and \( N_i \) are the electron and the ion densities of the observed emission line, respectively, and \( V \) is the observed volume (Peimbert 1967).

To determine \( T_0 \) and \( \tau^2 \) we need two different methods to derive \( T_e \): one that preferentially weighs the high-temperature regions and one that preferentially weighs the low-temperature regions (Peimbert 1967). In this paper we have used the temperature derived from the ratio of the [O III] \( \lambda\lambda 4363, 5007 \) lines, \( T_{(4363/5007)} \), which is given by

\[
T_{(4363/5007)} = T_0 \left[ 1 + \frac{1}{2} \left( \frac{91300}{T_0} - 3 \right) \tau^2 \right],
\] (5)

and the temperature derived from the ratio of the recombination lines of multiplet 1 of O II to the collisionally excited lines of [O III], which is given by (see Peimbert et al. 2004, eqs. [8]–[12])

\[
T([\text{O} \, \text{II} \, \text{rec}/\text{O} \, \text{III} \, \text{coll}]) = T_{(4649/5007)} = f_1(T_0, \tau^2).
\] (6)

Using the O recombination lines of region V, based on these equations, we obtain \( T_0 = 10.100 \) K and \( \tau^2 = 0.092 \pm 0.026 \). Since in this object most of the oxygen is twice ionized (see § 5.3), this \( \tau^2 \)-value is representative for the whole [O II] region.

It is also possible to derive the \( \tau^2 \)-value from the analysis of the helium lines (see § 5.1). The resulting values are \( \tau^2 = 0.060 \pm 0.026 \) and \( 0.056 \pm 0.045 \) for regions V and X, respectively. For region V we combine the oxygen and the helium determinations and adopt \( \tau^2 = 0.076 \pm 0.018 \); for region X we simply adopt the \( \tau^2 \) helium determination. The \( \tau^2 \)-values derived for regions V and X are somewhat larger than those derived for Galactic H II regions, which typically are in the 0.03–0.04 range (Esteban et al. 2005) but are similar to those derived in giant extragalactic H II regions (Esteban et al. 2002; Peimbert 2003).

### 5. IONIC CHEMICAL ABUNDANCES

#### 5.1. Helium Ionic Abundances

To obtain values of He\(^{++}/\)H\(^+\) we need a set of effective recombination coefficients for the He and H lines, the contribution due to collisional excitation to the helium line intensities, and an estimate of the optical depth effects for the helium lines. The recombination coefficients used were those by Storey & Hummer (1995) for H and those by Smits (1996) and Benjamin et al. (1999) for He. The collisional contribution was estimated from Sawey & Berrington (1993) and Kingdon & Ferland (1995). The optical depth effects in the triplet lines were estimated from the computations by Benjamin et al. (2002).

Before using the helium lines, much in the same way as we do for hydrogen lines, we need to correct them for underlying absorption and, in the cases of \( \lambda\lambda 3889 \) and \( 4713 \), for blends. To correct the blue lines, \( \lambda < 5000 \) \AA, for underlying absorption we used the values determined by González Delgado et al. (1999), and for the redder lines we used values determined by M. Cerviño (2005, private communication) based on the paper by González Delgado et al. (2005). It should be noted that the underlying absorption in the helium lines scales, in the same way as it does in the hydrogen lines, as a fraction of the correction to H\(\beta\). After discarding the lines that could not be easily unblended or those for which there is no accurate atomic data, the remaining lines are presented in Table 4.

We have many measured helium lines, each of them with a different dependence on temperature and density. In principle, one can find He I line ratios that will allow measurements of temperature or density. In practice, the dependence of each ratio is weak, and each ratio depends simultaneously on \( T_0, \tau^2, N_e, \) and \( T_{3889} \), giving the determinations obtained from any one ratio large error bars. In order to optimize our data we used a maximum
| λ (Å) | Identification | Region V | Region X |
|------|----------------|----------|----------|
|      |                | F(λ)^a  | I(λ)^b  | F(λ)^c | I(λ)^d |
| 3634 | He i           | 0.12     | 0.18 ± 0.07 | ... | ... |
| 3687 | H19            | 0.42     | 0.62 ± 0.12 | ... | ... |
| 3692 | H18            | 0.51     | 0.75 ± 0.13 | ... | ... |
| 3697 | H17            | 0.53     | 0.77 ± 0.14 | ... | ... |
| 3704 | H16            | 0.85     | 1.24 ± 0.17 | 1.01 | 1.31 ± 0.29 |
| 3712 | H15            | 0.76     | 1.10 ± 0.16 | 0.93 | 1.21 ± 0.26 |
| 3722 | H14            | 1.14     | 1.64 ± 0.20 | 1.12 | 1.44 ± 0.30 |
| 3726 | [O ii]         | 26.90    | 38.90 ± 1.00 | 46.80 | 60.40 ± 2.00 |
| 3729 | [O ii]         | 37.80    | 54.60 ± 1.20 | 66.90 | 86.30 ± 2.50 |
| 3734 | H13            | 1.28     | 1.85 ± 0.21 | 1.32 | 1.70 ± 0.33 |
| 3750 | H12            | 1.44     | 2.06 ± 0.22 | 2.68 | 3.43 ± 0.47 |
| 3771 | H11            | 2.02     | 2.87 ± 0.26 | 2.32 | 2.95 ± 0.44 |
| 3798 | H10            | 2.49     | 3.51 ± 0.28 | 3.81 | 4.82 ± 0.55 |
| 3820 | He i           | 0.42     | 0.58 ± 0.12 | 0.91 | 1.15 ± 0.27 |
| 3835 | H9             | 4.03     | 5.61 ± 0.36 | 4.29 | 5.39 ± 0.58 |
| 3869 | [Ne iii]       | 25.30    | 34.70 ± 0.90 | 21.90 | 27.30 ± 1.30 |
| 3889 | H8 + He i      | 11.60    | 16.10 ± 0.60 | 13.90 | 17.10 ± 1.00 |
| 3967 | [Ne iii] + H7 + He i | 19.00 | 25.40 ± 0.70 | 18.90 | 23.00 ± 1.20 |
| 4026 | He i           | 1.21     | 1.60 ± 0.18 | 1.40 | 1.69 ± 0.31 |
| 4069 | [S ii]         | 0.75     | 0.97 ± 0.14 | ... | ... |
| 4076 | [S ii]         | 0.17     | 0.22 ± 0.07 | ... | ... |
| 4101 | He i           | 19.20    | 24.70 ± 0.70 | 20.20 | 24.00 ± 1.20 |
| 4144 | He i           | 0.19     | 0.24 ± 0.07 | ... | ... |
| 4146 | O ii + Ne ii   | 0.13     | 0.16 ± 0.06 | ... | ... |
| 4192 | O ii           | 0.12     | 0.15 ± 0.05 | ... | ... |
| 4267 | C ii           | 0.07     | 0.09 ± 0.02 | ... | ... |
| 4340 | H7             | 39.20    | 47.00 ± 1.00 | 41.40 | 46.90 ± 1.70 |
| 4363 | [O iii]        | 4.87     | 5.79 ± 0.33 | 4.21 | 4.73 ± 0.52 |
| 4388 | He i           | 0.32     | 0.46 ± 0.09 | ... | ... |
| 4471 | He i           | 3.48     | 3.97 ± 0.27 | 3.50 | 3.82 ± 0.45 |
| 4591 | O ii           | 0.06     | 0.07 ± 0.02 | ... | ... |
| 4639 | O ii           | 0.10     | 0.11 ± 0.03 | ... | ... |
| 4649 | O ii           | 0.06     | 0.06 ± 0.02 | ... | ... |
| 4658 | [Fe iii]       | 0.23     | 0.24 ± 0.06 | ... | ... |
| 4711 | [Ar iv] + He i | 0.83     | 0.86 ± 0.12 | 0.26 | 0.27 ± 0.11 |
| 4740 | [Ar iv]        | 0.31     | 0.32 ± 0.07 | ... | ... |
| 4861 | H7             | 100.00   | 99.10 ± 1.30 | 100.00 | 99.10 ± 2.30 |
| 4922 | He i           | 1.07     | 1.04 ± 0.12 | 1.17 | 1.14 ± 0.23 |
| 4959 | [O iii]        | 183.00   | 177.00 ± 2.00 | 147.67 | 144.00 ± 3.00 |
| 5007 | [O iii]        | 557.00   | 535.00 ± 4.00 | 439.00 | 426.00 ± 5.00 |
| 5016 | He i           | 2.55     | 2.40 ± 0.19 | 2.77 | 2.65 ± 0.35 |
| 5048 | He i           | 0.16     | 0.17 ± 0.05 | ... | ... |
| 5270 | [Fe iii]       | 0.08     | 0.07 ± 0.03 | ... | ... |
| 5517 | [Cl iii]       | 0.48     | 0.39 ± 0.07 | 0.47 | 0.40 ± 0.13 |
| 5537 | [Cl iii]       | 0.39     | 0.31 ± 0.06 | 0.29 | 0.25 ± 0.10 |
| 5755 | [N ii]         | 0.22     | 0.16 ± 0.04 | ... | ... |
| 5876 | He i           | 15.80    | 11.40 ± 0.40 | 14.20 | 11.20 ± 0.70 |
| 6151 | C ii           | 0.08     | 0.05 ± 0.02 | ... | ... |
| 6312 | [S ii]         | 2.90     | 1.88 ± 0.14 | 2.68 | 1.96 ± 0.27 |
| 6548 | [N ii]         | 2.37     | 1.46 ± 0.12 | 3.35 | 2.39 ± 0.29 |
| 6563 | Ho             | 462.00   | 285.00 ± 2.00 | 401.00 | 285.00 ± 4.00 |
| 6584 | [N ii]         | 8.33     | 5.12 ± 0.23 | 10.00 | 7.10 ± 0.50 |
| 6678 | He i           | 5.25     | 3.17 ± 0.17 | 4.20 | 2.94 ± 0.32 |
| 6716 | [S ii]         | 11.20    | 6.70 ± 0.26 | 14.80 | 10.30 ± 0.60 |
| 6731 | [S ii]         | 8.42     | 5.02 ± 0.22 | 10.30 | 7.17 ± 0.50 |
| 6734 | C ii           | 0.11     | 0.07 ± 0.03 | ... | ... |
| 7065 | He i           | 4.42     | 2.50 ± 0.15 | 3.34 | 2.23 ± 0.27 |
| 7136 | [Ar iii]       | 16.50    | 9.20 ± 0.29 | 13.70 | 9.06 ± 0.55 |
| 7281 | He i           | 1.21     | 0.66 ± 0.07 | 0.75 | 0.49 ± 0.12 |
| 7320 | [O ii]         | 3.22     | 1.74 ± 0.12 | 3.36 | 2.18 ± 0.27 |

**TABLE 2**

**Line Intensities for Regions V and X**
likelihood method (MLM) to search for the physical and chemical conditions ($T_0$, $t^2$, $\tau_{3889}$, and He$^+/H^+$) that would give us the best simultaneous fit to all the measured lines (see Peimbert et al. 2000).

For these objects the MLM cannot determine the electron density with high enough accuracy to be useful; therefore, we have adopted the electron densities derived from collisionally excited lines. Based on Table 3 we adopted $N_e = 175 \pm 30$ and $30 \pm 30$ cm$^{-3}$ for regions V and X, respectively, to help with the determinations.

To help break the degeneracy on $T_0$ and $t^2$ we need to use an additional temperature. Since $T$(He $i$) preferentially weighs the low-temperature regions, we used a temperature that preferentially weighs the high-temperature regions (see § 4.2). In order for this temperature to be representative of the whole region we used a weighted average of $T([O ii])$ and $T([O iii])$ (Peimbert et al. 2002); for region V we used $T([O iii] + [O ii]) = 12,000$ K, and for region X we used $T([O iii] + [O ii]) = 12,250$ K.

From these line intensities, densities, temperatures, and the MLM we obtained the He abundances presented in Table 5, $t^2 = 0.060 \pm 0.026$ for region V and $t^2 = 0.056 \pm 0.045$ for region X.

5.2. C and O Ionic Abundances from Recombination Lines

The C$^+$ abundance was derived from multiplet 1 of O $\Pi$ (Peimbert et al. 1993; Storey 1994). The multiplet consists of eight lines, and the sum of their intensities, $I$(sum), normalized to $I$(H$\beta$), is independent of the electron density. On the other hand, the normalized intensity of each of the eight lines does depend on the electron density (Ruiz et al. 2003). It is rarely possible to measure all the lines of this multiplet, and frequently it is necessary to estimate the intensities of the unobserved (or blended) lines.

As with C $\Pi$, we only observe O $\Pi$ recombination lines on region V. Of the eight lines of multiplet 1 we only detect four, which, due to the dispersion of our observations, are blended into two pairs, $\lambda\lambda$4639+42 and 4649+51.

Ruiz et al. (2003) found that for typical H $\Pi$ region densities, the relative intensities of the lines of the multiplet deviate from the LTE computation predictions. In order to determine what fraction of the intensity of the whole multiplet is emitted in these four lines, it is necessary to determine the density dependence of each of these lines. Ruiz et al. present the density dependence of $I$(4649)/$I$(sum). In order to determine the density relations for all the lines of the multiplet, in Figures 4, 5, 6, and 7 we present plots of the data listed by Ruiz et al. in their Table 8 for the four sets of lines of multiplet 1 that originate in a given upper level (note that our Fig. 7 is the same as Fig. 2 by Ruiz et al.). From Figures 4–7 it can be seen that the intensity of the lines that originate in the 3$p^3\,4D_{3/2}$ and 3$p^3\,4D_{5/2}$ energy levels decreases with increasing local density, while the intensity of those lines that originate in the 3$p^3\,4D_{7/2}$ level increases with increasing density. This is because of collisional redistribution, which increases the population of the high statistical weight levels at the expense of the low statistical weight ones. Note that the intensity of the lines that originate

### Table 2—Continued

| $\lambda$ (Å) | IDENTIFICATION | Region V | Region X |
|---------------|----------------|----------|----------|
|               |                | $F(\lambda)^a$ | $I(\lambda)^b$ | $F(\lambda)^c$ | $I(\lambda)^d$ |
| 7330          | [O ii]         | 2.29     | 1.24 ± 0.10 | 2.97     | 1.92 ± 0.25 |
| 7751          | [Ne iii]       | 4.36     | 2.22 ± 0.14 | ...      | ...        |
| 8502          | Pa16           | 0.87     | 0.40 ± 0.06 | ...      | ...        |
| 8542          | Pa15           | 1.28     | 0.59 ± 0.07 | ...      | ...        |
| 8596          | Pa14           | 1.19     | 0.55 ± 0.06 | ...      | ...        |
| 8665          | Pa13           | 2.17     | 0.99 ± 0.09 | ...      | ...        |
| 8750          | Pa12           | 2.16     | 0.97 ± 0.08 | ...      | ...        |

Notes.—For regions V and X, log $[E(W/H)/] = 225$ and 215, respectively, where $E(W/H)/$ is the equivalent width in emission given in angstroms. The logarithmic reddening correction, $C(W/H)/$, is $0.64 ± 0.05$ for region V and $0.45 ± 0.05$ for region X.

a $F(\lambda)$ is the observed flux in units of $100.00 = 1.015 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$.
b $I(\lambda)$ is the reddening-corrected flux in units of $100.00 = 4.43 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$.
c $F(\lambda)$ is the observed flux in units of $100.00 = 3.73 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$.
d $I(\lambda)$ is the reddening-corrected flux in units of $100.00 = 1.050 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$.

### Table 3

| Densities and Temperatures |
|----------------------------|
| LINE | REGION V | REGION X |
|------|----------|----------|
|      | Densities (cm$^{-3}$) | Temperatures (K) | Densities (cm$^{-3}$) | Temperatures (K) |
| N II | ... | 15500 ± 2500 | ... | ... |
| O II | 190 ± 30 | 13000 ± 1000 | 30 ± 30 | 13300 ± 900 |
| S II | 90 ± 75 | 11500 ± 2000 | <100 | ... |
| O III | ... | 11900 ± 250 | ... | 12000 ± 400 |
| Cl III | <1000 | ... | <1000 | ... |
from the $3p^4D_{5/2}$ energy level depend weakly on the electron density. Based on Figures 4–7 and a relationship of the type

$$\frac{[I(\text{line})]}{[I(\text{sum})]}_{\text{obs}} = \frac{[I(\text{line})]}{[I(\text{sum})]}_{\text{LTE}} + \frac{[I(\text{line})]/[I(\text{sum})]_{\text{LTE}}}{[1 + N_e(\text{FL})/N_e(\text{crit})]} - [I(\text{line})]/[I(\text{sum})]_{\text{LTE}},$$

we have obtained the following equations:

$$\frac{[I(4651 + 74)]}{[I(\text{sum})]_{\text{obs}} = 0.101 + \frac{0.144}{[1 + N_e(\text{FL})/1325]},$$

(8)

$$\frac{[I(4639 + 62 + 96)]}{[I(\text{sum})]_{\text{obs}} = 0.201 + \frac{0.205}{[1 + N_e(\text{FL})/1325]},$$

(9)

$$\frac{[I(4642 + 76)]}{[I(\text{sum})]_{\text{obs}} = 0.301 - \frac{0.057}{[1 + N_e(\text{FL})/1325]},$$

(10)

$$\frac{[I(4649)]}{[I(\text{sum})]_{\text{obs}} = 0.397 - \frac{0.292}{[1 + N_e(\text{FL})/1325]},$$

(11)

where the first term on the right-hand side corresponds to the LTE ratio presented by Wiese et al. (1996) and the second term takes into account the deviation from LTE. The intensity of the lines originating from the same upper level is constant and depends only on the ratio of the Einstein $A$-coefficients for each level; thus, $I(4651)/I(4674)$ is 0.844±0.156, $I(4639)/I(4662)$:

$I(4696)$ is 0.455±0.039, and $I(4642)/I(4676)$ is 0.742±0.258. Since $I(4649)$ is the only line originating from the $3p^4D_{5/2}$ upper level, it will contain all the photons originating from this level.

Based on equations (8)–(11), the relative intensities of the lines originating from the same upper level, and the O ii lines presented in Table 2, we have determined the value of $I(\text{sum})$ for multiplet 1, which amounts to $I(\text{sum})/I(H\beta) = 0.0023$. We have derived the O$^{++}$ abundance presented in Table 5 from $I(\text{sum})$ and the effective recombination coefficient for multiplet 1 computed by Storey (1994) under the assumption of case B for $Te = 10,000$ K and $N_e = 100$ cm$^{-3}$.

### 5.3. Ionic Abundances from Collisions Excited Lines

The values presented in Table 6 for $t^2 = 0.00$ were derived with the IRAF task abund, using only the low- and medium-ionization zones. The task abund requires as inputs a temperature and a density for each zone as well as the intensities of the observed collisionally excited lines relative to Hβ. These values are combined with a model of a five-, six-, or eight-level ion to determine the abundances. The low- and medium-ionization zones of abund correspond to the low- and high-ionization zones of this paper. For region V we used $T_{\text{low}} = 13,000$ K, $T_{\text{high}} = 11,900$ K, and $N_{e \text{low}} = N_{e \text{high}} = 175$ cm$^{-3}$; and for region X we used $T_{\text{low}} = 13,300$ K, $T_{\text{high}} = 12,000$ K, and $N_{e \text{low}} = N_{e \text{high}} = 30$ cm$^{-3}$.

To derive the abundances for $t^2 > 0.00$ we used the abundances for $t^2 = 0.00$ corrected by the formulation for $t^2 > 0.00$ presented by Peimbert & Costero (1969; see also Peimbert et al. 1996).
To derive abundances for other $r^2$-values it is possible to interpolate or to extrapolate the values presented in Table 6.

6. TOTAL ABUNDANCES

To obtain the C and N gaseous abundances the following equations were adopted:

$$\frac{N(C)}{N(H)} = \text{ICF}(C) \frac{N(C^{++})}{N(H^+)}; \quad (12)$$

$$\frac{N(N)}{N(H)} = \text{ICF}(N) \frac{N(N^{+})}{N(H^+)}; \quad (13)$$

where ICF is the ionization correction factor. The value of ICF(C) was obtained from Garnett et al. (1995) and amounts to 0.07 dex. That of ICF(N) was obtained from the models by Moore et al. (2004) and amounts to 1.13 dex for region V and 0.91 dex for region X. Note that the value of ICF(N) predicted by Peimbert & Costero (1969) is given by $N(O)/N(O^+)$ and amounts to 0.97 dex for region V and 0.75 dex for region X; the ICF(N) formula by Peimbert & Costero is a very good approximation for H ii regions with a low degree of ionization but becomes only fair for H ii regions with a high degree of ionization. The ICF(N) for models in which a large fraction of the ionizing photons escape from the H ii region becomes even larger than those predicted by the models by Moore et al. (2004); see, for example, the results for NGC 346 obtained by Relano et al. (2002).

The gaseous abundances for O and Ne were obtained from the following equations (Peimbert & Costero 1969):

$$\frac{N(O)}{N(H)} = \frac{N(O^+)}{N(O^{++})} + \frac{N(O^{++})}{N(H^+)}; \quad (14)$$

and

$$\frac{N(\text{Ne})}{N(H)} = \left[ \frac{N(O^+)+N(O^{++})}{N(O^{++})} \right] \frac{N(\text{Ne}^{++})}{N(H^+)}; \quad (15)$$

The gaseous abundances of S, Cl, and Ar were obtained from the following equations:

$$\frac{N(S)}{N(H)} = \text{ICF}(S) \frac{N(S^+)+N(S^{++})}{N(H^+)}; \quad (16)$$

$$\frac{N(\text{Cl})}{N(H)} = \text{ICF}(\text{Cl}) \frac{N(\text{Cl}^{++})}{N(H^+)}; \quad (17)$$

$$\frac{N(\text{Ar})}{N(H)} = \text{ICF}(\text{Ar}) \frac{N(\text{Ar}^{++})+N(\text{Ar}^{+3})}{N(H^+)}; \quad (18)$$

The values of ICF(S) were estimated from the models by Garnett (1989) and amount to 0.22 dex for region V and 0.10 dex for region X. Those of ICF(Cl) amount to 0.05 dex for regions V and X and were obtained by averaging the observed values of $N(\text{Cl}^{++}+\text{Cl}^{+3})/N(\text{Cl}^{+})$ obtained for the Orion Nebula, 30 Doradus, and NGC 3576 (Esteban et al. 2004; Peimbert 2003; Garcia-Rojas et al. 2004). The ionization correction factor due to the Ar$^+$ fraction was estimated from $\text{ICF}(\text{Ar}) = 1/[1 - O^+/O]$.
### TABLE 6
**Ionic Abundance Determinations from Collisionally Excited Lines**

| Ion   | Region V | Region X |
|-------|----------|----------|
|       | $t^2 = 0.000$ | $t^2 = 0.076 \pm 0.018$ | $t^2 = 0.000$ | $t^2 = 0.054 \pm 0.045$ |
| N$^+$ | 5.72 ± 0.08 | 5.92 ± 0.10 | 5.85 ± 0.07 | 5.99 ± 0.13 |
| O$^+$ | 7.11 ± 0.12 | 7.37 ± 0.13 | 7.26 ± 0.12 | 7.44 ± 0.19 |
| O$^{++}$ | 8.03 ± 0.03 | 8.29 ± 0.06 | 7.92 ± 0.05 | 8.10 ± 0.16 |
| Ne$^+$ | 7.30 ± 0.03 | 7.58 ± 0.07 | 7.18 ± 0.05 | 7.37 ± 0.17 |
| S$^+$ | 5.17 ± 0.07 | 5.37 ± 0.09 | 5.33 ± 0.06 | 5.47 ± 0.13 |
| S$^{++}$ | 6.36 ± 0.04 | 6.55 ± 0.06 | 6.37 ± 0.07 | 6.50 ± 0.13 |
| Cl$^{+}$ | 4.42 ± 0.05 | 4.66 ± 0.08 | 4.38 ± 0.10 | 4.55 ± 0.17 |
| Ar$^{+}$ | 5.76 ± 0.02 | 5.97 ± 0.05 | 5.75 ± 0.04 | 5.90 ± 0.14 |

**Note.**—In units of $12 + \log [N(X)/N(H)]$, gaseous content only.

### TABLE 7
**NGC 6822 V Gaseous Abundance Determinations**

| Element  | This Paper | Lequeux et al. (1979) | Hidalgo-Gámez et al. (2001) |
|----------|------------|-----------------------|-----------------------------|
|          | $t^2 = 0.000$ | $t^2 = 0.076$ | $t^2 = 0.000$ | $t^2 = 0.000$ |
| He$^+$   | 10.922 ± 0.010 | 10.909 ± 0.011 | 10.88 | 10.90 |
| C$^+$    | 8.01 ± 0.12 | 8.01 ± 0.12 | ... | ... |
| N$^{++}$ | 6.85 ± 0.15 | 7.05 ± 0.16 | 6.53 | 6.52 |
| O$^+$    | 8.37 ± 0.09 | 8.37 ± 0.09 | ... | ... |
| O$^{++}$ | 8.08 ± 0.03 | 8.34 ± 0.06 | 8.20 | 8.10 |
| Ne$^{++}$ | 7.35 ± 0.03 | 7.63 ± 0.07 | 7.54 | 7.32 |
| S$^{++}$ | 6.61 ± 0.05 | 6.80 ± 0.07 | ... | ... |
| Cl$^{+}$ | 4.47 ± 0.05 | 4.71 ± 0.08 | ... | ... |
| Ar$^{+}$ | 5.84 ± 0.03 | 6.06 ± 0.05 | ... | ... |

**Note.**—In units of $12 + \log [N(X)/N(H)]$.

|               | $a$ Recombination lines. | $b$ Collisionally excited lines. | $c$ This is the adopted value; note that the $t^2$-value implicitly includes information from the O $ii$ recombination lines. |

### TABLE 8
**NGC 6822 X Gaseous Abundance Determinations**

| Element  | This Paper | Lequeux et al. (1979) | Hidalgo-Gámez et al. (2001) |
|----------|------------|-----------------------|-----------------------------|
|          | $t^2 = 0.000$ | $t^2 = 0.054$ | $t^2 = 0.000$ | $t^2 = 0.000$ |
| He$^+$   | 10.923 ± 0.010 | 10.916 ± 0.011 | 10.92 | 11.0 |
| N$^{++}$ | 6.76 ± 0.16 | 6.90 ± 0.22 | 6.50 | 6.4 |
| O$^+$    | 8.01 ± 0.05 | 8.19 ± 0.16 | 8.27 | 8.12 |
| Ne$^{++}$ | 7.27 ± 0.05 | 7.46 ± 0.17 | 7.61 | 7.4 |
| S$^{++}$ | 6.51 ± 0.06 | 6.64 ± 0.13 | ... | ... |
| Cl$^{+}$ | 4.43 ± 0.10 | 4.60 ± 0.17 | ... | ... |
| Ar$^{+}$ | 5.84 ± 0.05 | 5.99 ± 0.14 | ... | ... |

**Note.**—In units of $12 + \log [N(X)/N(H)]$.

| $a$ Recombination line. | $b$ Collisionally excited lines. |
TABLE 9  
NGC 6822 V, NGC 346, 30 Doradus, Orion Nebula, and Solar Total Abundances

| Element | NGC 6822 V | NGC 346 | 30 Doradus | Orion Nebula | Sun |
|---------|------------|---------|------------|--------------|-----|
| $12 + \log(\text{He}/\text{H})$ | $10.909 \pm 0.011$ | $10.900 \pm 0.003$ | $10.928 \pm 0.003$ | $10.988 \pm 0.003$ | $10.98 \pm 0.02$ |
| $12 + \log(\text{O}/\text{H})$ | $8.42 \pm 0.06$ | $8.15 \pm 0.06$ | $8.59 \pm 0.05$ | $8.73 \pm 0.03$ | $8.66 \pm 0.05$ |
| log(C/O) | $-0.31 \pm 0.13$ | $-0.87 \pm 0.08$ | $-0.45 \pm 0.05$ | $-0.21 \pm 0.04$ | $-0.27 \pm 0.10$ |
| log(N/O) | $-1.37 \pm 0.17$ | $-1.34 \pm 0.15$ | $-1.24 \pm 0.08$ | $-1.00 \pm 0.10$ | $-0.88 \pm 0.12$ |
| log(Fe/O) | $-0.79 \pm 0.09$ | $-0.83 \pm 0.06$ | $-0.76 \pm 0.06$ | $-0.68 \pm 0.08$ | $-0.82 \pm 0.09$ |
| log(S/O) | $-1.62 \pm 0.09$ | $-1.59 \pm 0.12$ | $-1.60 \pm 0.10$ | $-1.51 \pm 0.05$ | $-1.52 \pm 0.08$ |
| log(Cl/O) | $-3.71 \pm 0.10$ | ... | $-3.67 \pm 0.12$ | $-3.40 \pm 0.05$ | $-3.43 \pm 0.06$ |
| log(AR/O) | $-2.26 \pm 0.08$ | $-2.33 \pm 0.10$ | $-2.33 \pm 0.10$ | $-2.11 \pm 0.06$ | $-2.48 \pm 0.08$ |
| log(Fe/O) | $-1.41 \pm 0.10$ | $-1.41 \pm 0.10$ | $-1.41 \pm 0.10$ | $-1.23 \pm 0.20$ | $-1.21 \pm 0.06$ |

Notes:—Gaseous abundances for the H II regions. The O and C abundances have been corrected for the fractions of these elements trapped in dust grains; see text.

1. Gaseous abundances; values for $t^2 = 0.076 \pm 0.018$ obtained in this paper, with the exception of the value of Fe/O, which comes from stellar data (Venn et al. 2001).
2. Values for $t^2 = 0.022$ from Dufour et al. (1982), Peimbert et al. (2000, 2002), and Relaño et al. (2002). The value of Fe/O comes from stellar data (Venn 1999; Rolleston et al. 2003; Hunter et al. 2005).
3. Values for $t^2 = 0.033$ from Peimbert (2003).
4. Values for $t^2 = 0.024$ from Cunha & Lambert (1994) and Esteban et al. (2004). The O and C abundances have been increased by 0.08 and 0.10 dex, respectively, to take into account the fractions of these elements trapped in dust grains. The CI abundance has been decreased by 0.13 dex due to an error of $t^2 = 1.00$ dex in the determination of the CI/H ratio.
5. From Christensen-Dalsgaard (1998) and Asplund et al. (2005).

Based on the previous considerations, we present the total gaseous abundances of regions V and X in Tables 7 and 8, respectively. The errors for region X are larger than those for region V because the brightness of region X is about 3 times smaller than that of region V. Within the errors the abundances of both regions are similar. We need observations of higher quality than those presented in this paper to establish the presence of abundance variations among H II regions in NGC 6822.

In Table 9 we present the adopted total abundances for NGC 6822. To obtain the total O and C abundances we have to add a correction to the gaseous abundance due to the presence of dust. Following Esteban et al. (1998) these corrections amount to 0.08 dex for O and 0.10 dex for C.

We have also computed the hydrogen, helium, and heavy elements by mass for NGC 6822 V; they amount to $X = 0.7501$, $Y = 0.2433$, and $Z = 0.0066$. The Z-value was computed from the C, N, O, Ne, and Fe abundances (see Table 9, where the Fe abundance comes from stellar data by Venn et al. 2001) and assuming that they constitute 83.3% of the total Z-value. This fraction was obtained by assuming that all the other heavy elements in NGC 6822 present the same abundances relative to O as in the Sun, as presented by Asplund et al. (2005).

7. DISCUSSION

7.1. Comparison with Other Nebular Abundance Determinations

There have been seven O/H determinations for Hubble V, carried out by Smith (1975), Lequeux et al. (1979), Talent (1980), Peimbert & Spinrad (1970), Pagel et al. (1980), Skillman et al. (1989), and Hidalgo-Gámez et al. (2001), which amounted to $12 + \log(O/H) = 8.45, 8.28, 8.20, 8.10, 8.19, 8.20,$ and 8.10, respectively; these determinations were made based on the $T(O iii)$ temperature and under the assumption that $t^2 = 0.00$. Statistical errors are typically about 0.1 dex, so to a first approximation there is good agreement among the seven determinations. A second look reveals a systematic difference: the first three determinations were made with the image intensified dissector scanner (IIDS) and yield an average value of 8.31 dex, while the other four were made with other detectors and yield an average value of 8.15 dex; the difference is real and is mainly due to the nonlinearity of the IIDS detector (Peimbert & Torres-Peimbert 1987).

In Tables 7 and 8 we compare our determinations with those of Lequeux et al. (1979) and Hidalgo-Gámez et al. (2001) for $t^2 = 0.00$. As expected, our values for O/H and Ne/H are in better agreement with those by Hidalgo-Gámez et al. (2001). As mentioned above, the reason is the nonlinearity of the IIDS detector, which increases the difference between weak lines and strong lines, thus yielding lower temperatures and consequently larger values of O/H and Ne/H. For region V this nonlinearity also yields lower values of He+/H+ because the helium line intensities are weaker than the H line intensities. For region X the He+/H+ differences are not significant because the observational errors are larger than the differences predicted by the nonlinearity. The smaller errors for region V than for region X are due to the higher luminosity of region V, as can be seen in Table 2. Due to the smaller errors in the line intensities of region V, we took the abundances of this region as representatives of the whole galaxy.

7.2. Comparison with Stellar Abundance Determinations

The stars and H II regions of NGC 6822 have reliable O/H determinations that can be compared. In Table 10 we present the O/H abundances derived in this paper for Hubble V with those derived by Venn et al. (2001) for two A-type supergiants; the A supergiants were formed a few million years ago, so we expect them to have the same abundances as the H II regions. We find excellent agreement between the stellar values of O/H and those found using recombination lines; alternatively, the agreement with the values derived using collisionally excited lines ($t^2 = 0.00$) is poor. In addition, based on three B supergiant stars in NGC 6822, Muschielok et al. (1999) find a value of Fe/H of $-0.5 \pm 0.2$ dex relative to the Sun, in excellent agreement with the results of Venn et al. (2001) for two A-type supergiants.

7.3. Comparison with the Magellanic Clouds, the Orion Nebula, and the Sun

Also in Table 9 we present the Orion Nebula and the solar abundances for comparison. For the Orion Nebula, the value for
The high N/O ratio places NGC 6822 on the plateau formed by the Galaxy, while the H II region O/H abundances derived from collisionally excited lines (assuming $T(4363/5007)$) are in very good agreement with the O/H ratios derived from A-type supergiants, while the O/H abundances derived from collisionally excited lines are not. This result is qualitatively equivalent to that found for the solar vicinity by Esteban et al. (2004) and Carigi et al. (2005a); these authors find that the H II region O/H recombination abundances are in agreement with the O/H solar abundances after considering the O/H enrichment predicted by a chemical evolution model of the Galaxy, while the H II region O/H abundances derived from collisionally excited lines (assuming $T^2 = 0.00$) are not.

8. CONCLUSIONS

We show that the ratios of the lines of multiplet 1 of O II are not constant, but instead they depend on density. Only at high densities do they coincide with the ratios predicted using LTE. The same arguments can probably be made for most recombination lines from other multiplets of heavy elements.

We present a set of empirical equations to determine the O abundances from recombination lines of multiplet 1 of O II. These equations are useful for those cases in which not all the lines of the multiplet are observed.

We derive for the first time the C/H and O/H abundances of NGC 6822 based on recombination lines. We have also derived the N, O, Ne, S, Cl, and Ar abundances based on collisionally excited lines for $T^2 > 0.00$ and $T^2 > 0.00$ (the $T^2$ derived in this paper).

The O/H ratio derived from O recombination lines is 0.26 dex higher than that derived from [O II] $\lambda\lambda4363, 4959, 5007$ collisionally excited lines under the assumption that $T^2 = 0.00$ [that is, by adopting the $T(4363/5007)$ temperature].

We have found that in NGC 6822, the O/H abundance ratio derived from O recombination lines is in very good agreement with the O/H ratios derived from A-type supergiants, while the O/H abundances derived from collisionally excited lines are not. This result is qualitatively equivalent to that found for the solar vicinity by Esteban et al. (2004) and Carigi et al. (2005a); these authors find that the H II region O/H recombination abundances are in agreement with the O/H solar abundances after considering the O/H enrichment predicted by a chemical evolution model of the Galaxy, while the H II region O/H abundances derived from collisionally excited lines (assuming $T^2 = 0.00$) are not.

Table 10

| OBJECT        | $t^2 = 0.000$ | $t^2 > 0.000$ | A Supergiants | Sun + GCE$^c$ |
|---------------|--------------|--------------|---------------|--------------|
| NGC 6822...... | 8.16 ± 0.03  | 8.42 ± 0.06  | 8.36          | ...          |
| Solar vicinity| 8.59 ± 0.03  | 8.79 ± 0.05  | 8.59          | 8.79 ± 0.06  |
| SMC............ | 8.07 ± 0.02  | 8.15 ± 0.04  | 8.14          | ...          |
| WLM............ | 7.91          | ...          | 8.45          | ...          |

Note.—In units of $12 + \log (O/H)$, where it is assumed that 20% of the O in H II regions is trapped in dust grains.

a The H II regions are Hubble V for NGC 6822 (this paper), the H II region gradient for the Galaxy (Esteban et al. 2005), NGC 346 for the SMC (Peimbert et al. 2000), and the average of HM 7 and HM 9 for WLM (Lee et al. 2005).

b The data for NGC 6822 come from Venn et al. (2001), the data for the Galaxy and the SMC come from Venn (1999), and the data for WLM come from Lee et al. (2005).

c The measured solar value is 8.66 (Asplund et al. 2005), which corresponds to the ISM value 4.57 Gyr ago; Galactic chemical evolution models predict an increase in O/H of 0.13 dex since the Sun was formed.

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REFERENCES

Allende Prieto, C., Barklem, P. S., Lambert, D. L., & Cunha, K. 2004, A&A, 420, 183
Asplund, M., Grevesse, N., & Sauval, A. J. 2005, in ASP Conf. Ser. 336, Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, ed. F. N. Bash & T. G. Barnes (San Francisco: ASP), 25
Benjamin, R. A., Skillman, E. D., & Smitis, D. P. 1999, ApJ, 514, 307
———. 2002, ApJ, 569, 288
Carigi, L. 2003, MNRAS, 339, 825
Carigi, L., Colin, P., & Peimbert, M. 2005a, ApJ, submitted
Carigi, L., Peimbert, M., Esteban, C., & García-Rojas, J. 2005b, ApJ, 623, 213
Carigi, L., Colón, P., & Peimbert, M. 2005a, ApJ, submitted
Christensen-Dalsgaard, J. 1998, Space Sci. Rev., 85, 19
Cunha, K., & Lambert, D. L. 2003, ApJ, 581, 241
Davids, A. R., Storey, P. J., & Kisielius, R. 2000, A&AS, 142, 85
Dufour, R. J., Shields, G. A., & Talbot, R. J. 1982, ApJ, 252, 461
Esteban, C., García-Rojas, J., Peimbert, M., Peimbert, A., Ruiz, M. T., Rodríguez, M., & Carigi, L. 2005, ApJ, 618, L95
Esteban, C., Peimbert, M., García-Rojas, J., Ruiz, M. T., Peimbert, A., & Rodríguez, M. 2004, MNRAS, 355, 229
Esteban, C., Peimbert, M., Torres-Peimbert, S., & Escalante, V. 1998, MNRAS, 295, 401
Esteban, C., Peimbert, M., Torres-Peimbert, S., & Rodríguez, M. 2002, ApJ, 581, 241
Fragile, P. C., Murray, S. D., & Lin, D. N. C. 2004, ApJ, 617, 1077
García-Rojas, J., Esteban, C., Peimbert, M., Rodriguez, M., Ruiz, M. T., & Peimbert, A. 2004, ApJS, 153, 501
Garnett, D. R. 1989, ApJ, 345, 282
Garnett, D. R., Skillman, E. D., Dufour, R. J., Peimbert, M., Torres-Peimbert, S., Terlevich, R. J., Terlevich, E., & Shields, G. A. 1995, ApJ, 443, 64
González Delgado, R. M., Cerviño, M., Martins, L. P., Leitherer, C., & Hauschildt, P. H. 2003, MNRAS, 357, 945
González Delgado, R. M., Leitherer, C., & Heckman, T. M. 1999, ApJS, 125, 489
Hamuy, M., Suntzeff, N. B., Heathcote, S. R., Walker, A. R., Gigoux, P., & Phillips, M. M. 1994, PASP, 106, 566
Hamuy, M., Walker, A. R., Suntzeff, N. B., Gigoux, P., Heathcote, S. R., & Phillips, M. M. 1992, PASP, 104, 533
Hidalgo-Gámez, A. M., Olofsson, K., & Masegosa, J. 2001, A&A, 367, 388
Hunter, I., Dufour, P. L., Ryans, R. S. I., Lennon, D. J., Rolleston, W. R. J., Hubeny, I., & Lanz, T. 2005, A&A, 436, 687
Kingdon, J., & Ferland, G. 1995, ApJ, 442, 714
Lee, H., Skillman, E. D., & Venn, K. A. 2005, ApJ, 620, 223
Legrand, F., Tenorio-Tagle, G., Silich, S., Kunth, D., & Cerviño, M. 2001, ApJ, 560, 630
Lequeux, J., Peimbert, M., Rayo, J. F., Serrano, A., & Torres-Peimbert, S. 1979, A&A, 80, 155
Liu, X.-W., Storey, P. J., Barlow, M. J., Danziger, I. J., Cohen, M., & Bryce, M. 2000, MNRAS, 312, 585
Martin, C. L. 2003, in Rev. Mex. AA Ser. Conf., 17, 56
Moore, B. D., Hester, J. J., & Dufour, R. J. 2004, AJ, 127, 3484
Muschielok, B., et al. 1999, A&A, 352, L40
Pagel, B. E. J., Edmunds, M. G., & Smith, G. 1980, MNRAS, 193, 219
Peimbert, A. 2003, ApJ, 584, 735
Peimbert, A., Peimbert, M., & Luridiana, V. 2002, ApJ, 565, 668
Peimbert, M. 1967, ApJ, 150, 825
Peimbert, M., & Costero, R. 1969, Bol. Obs. Tonantzintla Tacubaya, 5, 3
Peimbert, M., Peimbert, A., & Ruiz, M. T. 2000, ApJ, 541, 688
Peimbert, M., Peimbert, A., Ruiz, M. T., & Esteban, C. 2004, ApJS, 150, 431
Peimbert, M., & Spinrad, H. 1970, A&A, 7, 311
Peimbert, M., Storey, P. J., & Torres-Peimbert, S. 1993, ApJ, 414, 626
Peimbert, M., & Torres-Peimbert, S. 1987, in Rev. Mex. AA Ser. Conf., 14, 540
Relaño, M., Peimbert, M., & Beckman, J. 2002, ApJ, 564, 704
Rolleston, W. R. J., Venn, K. A., Tolstoy, E., & Dufour, P. L. 2003, A&A, 400, 21
Ruiz, M. T., Peimbert, A., Peimbert, M., & Esteban, C. 2003, ApJ, 595, 247
Sawa, T., & Fujimoto, M. 2005, PASJ, 57, 429
Sawey, P. M. J., & Berrington, K. A. 1993, At. Data Nucl. Data Tables, 55, 81
Seaton, M. J. 1979, MNRAS, 187, 73P
Skillman, E. D., Terlevich, R., & Melnick, J. 1989, MNRAS, 240, 563
Smith, H. E. 1975, ApJ, 199, 591
Smits, D. P. 1996, MNRAS, 278, 683
Storey, P. J. 1994, A&A, 282, 999
Storey, P. J., & Hummer, D. G. 1995, MNRAS, 272, 41
Talent, D. L. 1980, Ph.D. thesis, Rice Univ.
Tenorio-Tagle, G., Silich, S., & Muñoz-Tuñón, C. 2003, in Rev. Mex. AA Ser. Conf., 18, 136
Trimble, V. 2000, in Allen’s Astrophysical Quantities, ed. A. N. Cox (New York: Springer), 578
Venn, K. A. 1999, ApJ, 518, 405
Venn, K. A., & Miller, L. 2002, in Rev. Mex. AA Ser. Conf., 12, 230
Venn, K. A., Tolstoy, E., Kauffer, A., & Kudritzki, R. P. 2004, in Carnegie Obs. Astrophys. Ser. 4, Origin and Evolution of the Elements, ed. A. McWilliam & M. Rauch (Cambridge: Cambridge Univ. Press), 58
Venn, K. A., et al. 2001, ApJ, 547, 765
Wiese, W. L., Fuhr, J. R., & Deters, T. M. 1996, Atomic Transition Probabilities of Carbon, Nitrogen, and Oxygen: A Critical Data Compilation (Washington: American Chem. Soc.; and Woodbury: AIP)
Wyder, T. K. 2001, AJ, 122, 2490