SMALL-SCALE BEHAVIOR OF THE PHYSICAL CONDITIONS AND THE ABUNDANCE DISCREPANCY IN THE ORION NEBULA1

Adal Mesa-Delgado, César Esteban, and Jorge García-Rojas

Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain; amd@ll.iac.es, cel@ll.iac.es, jogarcia@ll.iac.es

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ABSTRACT

We present the results of long-slit spectroscopy, in several positions, of the Orion Nebula. Our goal is to study the spatial distributions of a large number of nebular quantities, including line fluxes, physical conditions, and ionic abundances, at a spatial resolution of about 1". In particular, we have compared the O++ abundance determined from collisionally excited and recombination lines in 671 individual one-dimensional spectra covering different morphological zones of the nebula. We find that protoplanetary disks (proplyds) show prominent spikes of \( T_e ([N \text{ ii}]) \), which is probably produced by collisional deexcitation due to the high electron densities found in these objects. Herbig-Haro objects show also relatively high values of \( T_e ([N \text{ ii}]) \), but these are probably produced by local heating due to shocks. We also find that the spatial distribution of the pure recombination O ii and [O iii] lines is fairly similar. The abundance discrepancy factor (ADF) of O++ remains rather constant along the slit positions, except in some particular small areas of the nebula, such as at the locations of the most conspicuous Herbig-Haro objects. There is also an apparent slight increase of the ADF in the inner 40'' around \( \theta^1 \) Ori C. We find a negative radial gradient of \( T_e ([O \text{ ii}]) \) and \( T_e ([N \text{ ii}]) \) in the nebula, based on the projected distance from \( \theta^1 \) Ori C. In addition, the ADF of O++ seems to increase very slightly with the electron temperature. Finally, we estimate the value of the mean-square electron temperature fluctuation, the so-called \( r^2 \) parameter. Our results indicate that the hypothetical thermal inhomogeneities, if they exist, should be smaller than our spatial resolution element.

Subject headings: H ii regions — ISM: abundances — ISM: individual (Orion Nebula)

1. INTRODUCTION

Analysis of the spectrum of H ii regions makes it possible to determine the chemical composition of the ionized gas phase of the interstellar medium, from the solar neighborhood to the high-redshift universe. Therefore, this stands as an essential tool for our knowledge of the chemical evolution of the universe. In photoionized nebulae, the abundance of the elements heavier than He is usually determined from collisional excitation lines (CELs), whose intensity depends exponentially on the electron temperature, \( T_e \), of the gas. It was about 20 years ago when the first determinations of the C++ abundance from the intensity of the weak recombination line (RL) of C++ were made available for planetary nebulae (PNs). The comparison of the abundance obtained from C++ and from the CELs of this ion in the ultraviolet (UV) showed a difference that could be as large as a order of magnitude in some objects (e.g., French 1983; Rola & Stasińska 1994, Mathis & Liu 1999). Peimbert et al. (1993) were the first to determine the O++ abundance from the very weak RLs, obtaining the same qualitative result: the abundances obtained from RLs are higher than those determined by making use of CELs. This observational fact is currently known as the "abundance discrepancy" (AD) problem. In the last few years, our group has obtained a large data set of intermediate- and high-resolution spectroscopy of Galactic and extragalactic H ii regions using medium- and large-aperture telescopes (Esteban et al. 2002, 2005; García-Rojas et al. 2004, 2005, 2006, 2007; López-Sánchez et al. 2007). The general result of these works is that the O++/H+ ratio calculated from RLs is between 0.10 and 0.35 dex higher than the value obtained from CELs in the same objects. The value of the AD that we usually find in H ii regions is rather similar for all objects and ions and is much lower than the most extreme values found in PNs. The H ii region results obtained by our group are fairly different than those found for PNs, and they seem to be consistent with the predictions of the temperature fluctuations paradigm formulated by Peimbert (1967), as argued in García-Rojas (2006) and García-Rojas & Esteban (2007). In the presence of temperature fluctuations (parameterized by the mean square of the spatial variations of temperature, the so-called \( r^2 \) parameter), the AD can be naturally explained by the different temperature dependences of the intensity of RLs and CELs. The existence and origin of temperature fluctuations are still controversial problems and a challenge for our understanding of ionized nebulae. Recently, Tsamis & Péquignot (2005) and Stasińska et al. (2007) have proposed a hypothesis to the origin of the AD that is based on the presence of cold high-metallicity clumps of supernova ejecta still not mixed with the ambient gas of the H ii regions. This cold gas would produce most of the emission of the RLs, whereas the ambient gas of normal abundances would emit most of the intensity of the CELs.

Our group is interested in exploring the question of on what variable or physical process the AD depends, using different approaches. One of the most promising approaches is based on the study of the behavior of the AD factor at small spatial scales, something that has still not been explored in depth in nearby bright Galactic H ii regions. In this paper, we make use of deep intermediate-resolution long-slit spectroscopy of the Orion Nebula to study the dependence of the AD with respect to different nebular parameters: electron temperature and density, the local ionization state of the gas, the presence of high-velocity material, and its correlation with different morphological structures (e.g., proplyds, ionization fronts, globules, Herbig-Haro objects).

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1 Based on observations made with the 4.2 m William Herschel Telescope (WHT), operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatory del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

2 Current address: Instituto de Astronomía, UNAM, Apdo. Postal 70-264, 04510 México D.F., Mexico.
The spatial distribution of the physical conditions in the Orion Nebula has been investigated by several authors. Baldwin et al. (1991) obtained the density and temperature distributions at 21 and 14 points, respectively, along a 5' line west of 06 Ori C, finding a density gradient that decreases to the outskirts of the nebula and a constant value of $T_e$. Walter et al. (1992) determined electron densities, electron temperatures, and chemical abundances for 22 regions of the Orion Nebula. Using also data from the literature, these authors find radial gradients of the physical conditions, but with a positive slope in the case of the temperature determined from $[O \text{ iii}]$ lines. Pogge et al. (1992) obtained Fabry-Pérot images of the inner 6' of the nebula, covering several bright CELs, that were taken with an average seeing of about 1.8". Those authors present a density map obtained from the ratio of the $[S \text{ ii}]$ doublet that confirms the presence of a density gradient that reaches its highest point immediately south-southwest of the Trapezium stars, along with some localized density enhancements in the Orion bar and some Herbig-Haro objects. Very recently, Sánchez et al. (2007) have obtained an integral field spectroscopy mosaic of an area of 5' x 6' of the center of the Orion Nebula, with a spatial resolution of 2.7". The electron density map that they obtain is consistent with that obtained by Pogge et al. (1992) but richer in substructures, some of which are possibly associated with Herbig-Haro objects. Sánchez et al. (2007) also obtain an electron temperature map (derived from the line ratio of $[N \text{ ii}]$ lines) that shows clear spatial variations, which rise near the Trapezium and drop toward the outer zones of the nebula. However, an important drawback of the temperature map of Sánchez et al. is that it is based on non-flux calibrated spectra, and possible effects due to variations in the dust extinction distribution cannot be disregarded. O'Dell et al. (2003) obtained a high-resolution map of the electron temperature (derived from the line ratio of $[O \text{ iii}]$ lines) of a 160" x 160" field centered at the southwest of the Trapezium. The data were obtained from narrowband images taken with the WFPC of the Hubble Space Telescope (HST). Although they do not find a substantial radial gradient of $T_e$ in the nebula, O'Dell et al. (2003) report the existence of small-scale temperature variations down to a few arcseconds, which is compatible with the values of the temperature fluctuations parameter calculated from the AD determinations by Esteban et al. (2004). Rubin et al. (2003) obtained HST STIS long-slit spectroscopy at several slit positions on the Orion Nebula, analyzing the electron temperature and density spatial profiles with resolution elements of 0.5" x 0.5". These last authors do not find large-scale gradients of the physical conditions along the slits, but rather a relatively large point-to-point variation and some correlation of such variations with several small-scale structures.

The spatial mapping of the AD factor has been performed in few ionized nebulae, but largely for PNs. Liu et al. (2000), Garnett & Dinerstein (2001), and Krabbe & Copetti (2006) have found significant differences in the spatial profiles of the $O^{+}/H^+$ ratio derived by making use of RLS and CELs, and this suggests the presence of chemical inhomogeneities or additional mechanisms for producing the $O \text{ ii}$ lines in these objects. Tasnási et al. (2003) have performed the only available study so far of the spatial distribution of the AD factor in an H II region: 30 Doradus. However, considering the extragalactic nature of this object and the spatial sampling of 3.5" used by those authors, their final spatial resolution is very low: about 1 pc. In any case, Tasnási et al. (2003) find a rather constant AD factor along the zone covered with their observations, which is a quite different behavior than that observed in PNs.

In §§ 2 and 3 of this paper, we describe the observations, the data reduction procedure, and the aperture extraction and measurement of the emission lines. In § 4 we derive the physical conditions and the ionic abundances from both kinds of lines, CELs and RLS. In § 5 we present and discuss the spatial profiles of the physical conditions, the line fluxes, and the abundance discrepancy factor along the slit positions. In § 6 we discuss the large-scale radial distribution of some nebular properties along the nebula. In § 7 we explore possible correlations between the AD and different nebular parameters. In § 8 we address and estimate the possible temperature fluctuations inside the nebula. Finally, in § 9 we summarize our main conclusions.

2. OBSERVATIONS, DATA REDUCTION, AND EXTRACTION OF ONE-DIMENSIONAL SPECTRA

Intermediate-resolution spectroscopy was obtained on 2002 December 27 with the ISIS spectrograph at the 4.2 m William Herschel Telescope (WHT) of the Observatorio del Roque de los Muchachos (La Palma, Spain). Two different CCDs were used for the blue and red arms of the spectrograph: an EEV CCD with a configuration of 4096 x 2048 pixels, with a pixel size of 13.5 $\mu$m, in the blue arm, and a Marconi CCD with 4700 x 2148 pixels, with a pixel size of 13.5 $\mu$m, in the red arm. The dichroic prism used to separate the blue and red beams was set at 5400 Å. The slit was 3.7" long and 1.03" wide. Two gratings were used, the R1200B in the blue arm and the R316R in the red arm. These gratings give reciprocal dispersions of 17 and 62 Å $^{-1}$, and effective spectral resolutions of 0.86 and 3.81 Å, for the blue and red arms, respectively. The blue spectra cover the range from 4198 to 5048 Å, and the red ones from 5370 to 8690 Å. The spatial scale is 0.20" pixel$^{-1}$ in both arms. The average seeing during the observations was $\sim$1.2".

We observed five slit positions, covering different zones of the nebula and different position angles (see Fig. 1). These positions were chosen in order to cover different morphological structures, such as proplyds (158−323, 158−326, 159−350, 170−337, and 177−341), Herbig-Haro objects (HH 202, HH 203, HH 204, HH 529, and HH 530), and the Orion bar. Due to the high surface brightness of the nebula, a large number of individual short exposures were taken for each slit position and in each spectral range in order to achieve a good signal-to-noise ratio in the faint $C \text{ ii}$ and $O \text{ ii}$ RLS and to avoid saturating the brightest emission lines. The journal of observations can be found in Table 1. Note that the five slit positions are numbered as 1, 3, 4, 5, and 6; there was not actually a slit position number 2.

The spectra were wavelength-calibrated with a CuNe+CuAr lamp. The correction for atmospheric extinction was performed using the average curve for continuous atmospheric extinction at the Observatorio del Roque de los Muchachos. The absolute flux calibration was achieved by observations of the standard stars Feige 15, Feige 110, H600, and Hz 44. All the CCD frames were reduced using the standard IRAF3 TWODSPEC reduction package to perform bias correction, flat-fielding, cosmic-ray rejection, wavelength and flux calibration, and sky subtraction.

The extraction of one-dimensional spectra was done automatically through an IRAF script, using the apall1 task. First, we traced the apertures interactively by selecting the brightest object (star, proplyd, or Herbig-Haro object) in each two-dimensional (2D) spectrum. In all cases we adjusted a third-order spline function and obtained a typical rms value of the fit that was between 0.05 and 0.1 pixels. In the following step, we defined the apertures

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3 IRAF is distributed by the National Optical Astronomical Observatory, operated by the Associated Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.
to extract for each 2D spectrum by using the coefficients obtained in the aperture tracing. For all the slit positions, we extracted apertures with a size of 6 pixels in the spatial direction, which corresponds to an angular scale of 1.2"; the average seeing during the night. Therefore, each aperture covers a size of 1.2" × 1.03" in the spatial and spectral directions, respectively. At the distance of the Orion Nebula (450 pc; O'Dell 2001), 1" corresponds to a linear size of 0.0022 pc, 6.8 × 10⁻¹⁵ cm, or 450 AU. The slit center in the red arm is some pixels displaced with respect to the slit center in the blue arm; this effect has been corrected in the extraction procedure, ensuring the same spatial coverage in the blue and red ranges. We have discarded the apertures located near the edges of the CCDs, resulting in a final number of 154 apertures extracted—individual one-dimensional spectra—for each slit position except numbers 1 and 4. In these two cases a star, \( \theta^1 \) Ori A, fell into the slit, and we discarded the apertures that were contaminated by stellar emission (11 apertures in position 1 and 12 in position 4). In addition, the last 17 apertures at the northwest edge of position 4 were also discarded because the temperature-sensitive \([\text{O iii}]\) λ4363 line was not detected due to the faintness

![Fig. 1.— Our slit positions over a mosaic of a combination of WFPC2 images of the Orion Nebula, taken with different filters (O’Dell & Wong 1996).](image)

| Slit Position | R.A.\(^\text{a}\) (J2000.0) | Decl.\(^\text{a}\) (J2000.0) | P.A. (deg) | \( \Delta \lambda \) (Å) | Spectral Resolution (Å pixel⁻¹) | Exposure Time (s) |
|---------------|-----------------|-----------------|-----------|-----------------|-------------------------------|-----------------|
| 1...................... | 05 35 15.0       | -05 23 04       | 0         | 4198–5048       | 0.23                          | 30 × 60         |
| 2...................... | 05 35 22.4       | -05 25 09       | 147       | 4198–5048       | 0.84                          | 40 × 30         |
| 3...................... | 05 35 12.4       | -05 22 44       | 107       | 4198–5048       | 0.23                          | 31 × 60         |
| 4...................... | 05 35 15.8       | -05 23 33       | 50        | 4198–5048       | 0.84                          | 40 × 30         |
| 5...................... | 05 35 15.3       | -05 23 38       | 72        | 4198–5048       | 0.84                          | 20 × 100        |

\( \text{Note.—} \) Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

\( \text{a} \) Coordinates of the slit center.
of the spectra. The final total number of apertures extracted was 730.

For each slit position, we extracted additional one-dimensional spectra by collapsing the whole slit—the whole extension of the 154 individual apertures—but excluding different particular zones: (1) only those apertures contaminated by stellar emission; these will be designated as “whole-slit” spectra, or (2) the same zones as before, but also those apertures covering proplyds, Herbig-Haro objects, or having a very low surface brightness; these spectra are designated as “background-gas.” In Table 2, for each slit position, we summarize the number of apertures that are excluded due to stellar emission contamination or nondetection of the [O iii] λ4363 line (first row), the total number of usable apertures (second row), and the apertures that we consider representative of the background gas (third row).

3. EMISSION LINE SELECTION, FLUX MEASUREMENTS, AND REDDENING CORRECTION

The emission lines considered in our analysis are listed in Table 3. Each line was selected in order to satisfy one of the following criteria:

1. H i lines (H α, H β, and H γ), which are used to compute the reddening correction and to rescale the line intensity ratios of the red spectral range with respect to the blue one.

2. Ratios of CELs of various species, which are used to compute both physical conditions, such as using the auroral lines [O iii] λ4363 or [N ii] λ5754 to derive T e, or the [S ii] lines to derive n e, and ionic abundances.

3. Faint recombination lines of C ii and O ii, which are used to derive the C + + and O + abundances and to compute the abundance discrepancy factor for O + (via a comparison with the O + abundances from the CELs).

4. Some lines that are blended with other lines of interest.

Line fluxes were measured by applying a single or multiple (in the case of line blending) Gaussian profile fitting procedure, except in some apertures of positions 3 and 4, where the complex velocity field of the Herbig-Haro objects affects the line profiles and the Gaussian fit was not feasible. In these cases, the line intensities were measured by integrating all the flux included in the line profile between two given limits and over a local continuum estimated by eye. In general, there is a good agreement between both kinds of measurements within the adopted uncertainties. The observational errors associated with the line flux measurements was determined, following Castellanos et al. (2002), from the expression σ i = σ 0.1 [1 + EW/(N Δ i )] 1/2, where σ i is the error in the line flux, σ 0.1 represents the standard deviation of the continuum close to the measured emission line, N is the number of pixels used in the measurement of the line flux, EW is the line equivalent width, and Δ is the wavelength dispersion in units of Å pixel −1. The final uncertainty of the line intensity ratios is estimated to be typically about 1% if the ratio F (λ)/F (H β) ≥ 0.1, about 2% if 0.01 ≤ F (λ)/F (H β) ≤ 0.1, about 10% if 0.005 ≤ F (λ)/F (H β) ≤ 0.01, about 25% if 0.001 ≤ F (λ)/F (H β) ≤ 0.005, and about 40% if 0.0001 ≤ F (λ)/F (H β) ≤ 0.001. We do not consider lines weaker than 0.0001F (H β) (see below).

All the line intensities of a given aperture have been normalized to a particular H i recombination line present in each wavelength interval. For the blue spectra, the reference line was H β.

| Parameter                                                                 | Position 1 | Position 3 | Position 4 | Position 5 | Position 6 |
|--------------------------------------------------------------------------|------------|------------|------------|------------|------------|
| Number of excluded apertures                                             | 11         | ...        | 29         | ...        | ...        |
| Number of extracted apertures                                            | 143        | 154        | 125        | 154        | 154        |
| Background-gas zones                                                     | 1–60, 72–84, 90–143 | 85–154     | 25–50, 75–85 | 1–57, 62–74, 79, 154 | 1–40, 45–63, 70–154 |

* Contaminated by stellar emission or nondetection of the [O iii] λ4363 line.

b Summed for producing the whole-slit spectra.

c Summed for producing the background-gas spectra.

### Table 3

**Selected Lines**

| λ (Å)   | Ion   | Multiplet |
|---------|-------|-----------|
| 4267.15 | C ii  | 6         |
| 4340.47 | H i   | H γ       |
| 4363.21 | [O iii] | 2F       |
| 4638.86 | O ii  | 1         |
| 4640.64 | N iii | 2         |
| 4641.81 | O i   | 1         |
| 4643.06 | N ii  | 5         |
| 4649.13 | O i   | 1         |
| 4650.84 | O i   | 1         |
| 4661.63 | O ii  | 1         |
| 4711.37 | [Ar iv] | 1F       |
| 4861.33 | H i   | H β       |
| 4881.00 | [Fe ii] | 2F       |
| 4958.91 | [O iii] | 1F       |
| 5006.94 | [O iii] | 1F       |
| 5517.71 | [Cl i] | 1F       |
| 5537.88 | [Cl i] | 1F       |
| 5754.64 | [N ii] | 3F       |
| 6300.30 | [S i]  | 1F       |
| 6312.10 | [S ii] | 3F       |
| 6363.78 | [O i]  | 1F       |
| 6548.03 | [N ii] | 1F       |
| 6562.82 | H i   | H α       |
| 6583.41 | [N ii] | 1F       |
| 6716.47 | [S ii] | 2F       |
| 6730.85 | [S ii] | 2F       |
| 7135.78 | [Ar ii] | 1F       |
| 7319.19 | [O i]  | 2F       |
| 7330.20 | [O i]  | 2F       |
| 7751.10 | [Ar ii] | 2F       |
and for the red ones, the reference was Hα. To produce a final homogeneous set of line intensity ratios, all of them were rescaled to Hβ. The rescaling factor used in the red spectra was the theoretical Hα/Hβ ratio for the physical conditions of $T_e = 10,000$ K and $n_e = 1000$ cm$^{-3}$.

As can be expected, weak lines were not detected in all the apertures. To avoid bad weak-line measurements, we imposed three criteria to discriminate between real features and noise. The criteria are the following:

1. Line intensity peak over 2.5 times the sigma of the continuum (2.5 $\sigma$). The more usual criterion of 3 $\sigma$ was not adopted because several important lines that were clearly detected were discarded using that constraint.
2. $\text{FWHM}(\lambda) > 1.5 \times \text{FWHM}(H\alpha)$ or $\text{FWHM}(\lambda) < \text{FWHM}(H\alpha)/(1.5)$. These inequalities were used to discriminate between true emission lines and spurious features.
3. $I(\lambda) < 0.0001I(H\beta)$. This intensity was near the detection limit of our observations.

The reddening coefficient, $c(H\beta)$, was obtained by fitting the observed $H\gamma/H\beta$ ratio to the theoretical one predicted by Storey & Hummer (1995) for the nebular conditions determined in the slit position observed by Esteban et al. (2004). Following Esteban et al. (1998), we have used the reddening function, $f(\lambda)$, normalized at Hβ as derived by Costero & Peimbert (1970) for the Orion Nebula. In Figure 2, as an example, we show the spatial distribution of $c(H\beta)$ obtained for the apertures of slit position 6. The zone of the largest reddening at the left half of Figure 2 corresponds to the northeast portion of slit position 6. The reddening maps of O’Dell & Yusef-Zadeh (2000) and Sánchez et al. (2007) also show larger values at this zone, which is in the vicinity of the so-called Dark Bay. The typical uncertainty of $c(H\beta)$ is estimated to be about 0.05.

4. PHYSICAL CONDITIONS
AND CHEMICAL ABUNDANCES

4.1. Electron Temperatures and Densities

Nebular electron temperatures, $T_e$, and densities, $n_e$, have been derived from the usual CEL ratios, using the IRAF task ionfit. The methodology for the determination of the physical conditions was the following: an initial $T_e$-value of 10,000 K was assumed in order to derive a first approximation to $n_e([S\,\text{ii}])$; then the obtained $n_e$-value was used to compute $T_e([S\,\text{ii}])$ and $T_e([N\,\text{ii}])$; and finally, we iterated until convergence to compute the adopted values of $n_e$ and $T_e$. Uncertainties in the physical conditions were computed by propagating the errors in the analytical expression of $n_e$ computed by Castañeda et al. (1992) and the expression of $T_e$ given by equations (5.4) and (5.5) of Osterbrock & Ferland (2006). Although the expression derived by Castañeda et al. (1992) is only valid to a limited range of densities lower than $10^4$ cm$^{-3}$, it seems adequate for simply estimating the error propagation due to uncertainties in the computed temperatures and line ratios.

4.2. Ionic Abundances from CELs and RLs

Ionic abundances of N$^+$, O$^+$, O$^{++}$, S$^+$, S$^{++}$, and Ar$^{++}$ have been derived from CELs by making use of the IRAF task ionfit of the package nebular (Shaw & Dufour 1995) with updated atomic data (see García-Rojas et al. 2005). We have computed $n_e$ from the [S\,\text{ii}] 6717/6731 line ratio and $T_e$ from the nebular auroral [O\,\text{iii}] (4959 + 5007)/4363 and [N\,\text{ii}] (6548 + 6584)/5754 line ratios. The spatial distributions of the physical conditions are presented and discussed in §5.1. Although we include the [Cl\,\text{ii}] doublet in our set of selected lines, we do not use the lines in the analysis because the number of apertures with good determinations of the density-sensitive line ratio is rather low.

The methodology for the determination of the physical conditions was the following: an initial $T_e$-value of 10,000 K was assumed in order to derive a first approximation to $n_e([S\,\text{ii}])$; then the obtained $n_e$-value was used to compute $T_e([S\,\text{ii}])$ and $T_e([N\,\text{ii}])$; and finally, we iterated until convergence to compute the adopted values of $n_e$ and $T_e$. Uncertainties in the physical conditions were computed by propagating the errors in the analytical expression of $n_e$ computed by Castañeda et al. (1992) and the expression of $T_e$ given by equations (5.4) and (5.5) of Osterbrock & Ferland (2006). Although the expression derived by Castañeda et al. (1992) is only valid to a limited range of densities lower than $10^4$ cm$^{-3}$, it seems adequate for simply estimating the error propagation due to uncertainties in the computed temperatures and line ratios.

On the other hand, the high signal-to-noise ratio of the spectra has permitted us to detect and measure pure RLs of O\,\text{ii} and C\,\text{ii} in most of the apertures (see Fig. 3). These lines have the advantage that their relative intensity with respect to the H\,\text{i} lines depends weakly on $T_e$ and $n_e$, which avoids the problem of the presence of temperature variations along the line of sight, which can actually affect the abundance determinations from CELs, whose emissivities depend strongly on the $T_e$-value of the nebula.
Let \( I(\lambda) \) be the intensity of a RL of an element X, \( i \) times ionized, at wavelength \( \lambda \); then the abundance of the ionization state \( i + 1 \) of element X is given by

\[
\frac{N(X^{i+1})}{N(H^+)} = \frac{\bar{\lambda}(\lambda)}{4861} \frac{\alpha_{\text{eff}}(H\beta)}{\alpha_{\text{eff}}(\lambda)} \frac{I(\lambda)}{I(H\beta)},
\]

where \( \alpha_{\text{eff}}(\lambda) \) and \( \alpha_{\text{eff}}(H\beta) \) are the effective recombination coefficients for the line and for H\( \beta \), respectively. The \( \alpha_{\text{eff}}(H\beta)/\alpha_{\text{eff}}(\lambda) \) ratio is almost independent of the adopted temperatures and densities.

Following Esteban et al. (1998), we have considered the abundances obtained from the intensity of each individual line of multiplet 1 of O\( \mathrm{II} \) and the abundances from the estimated total intensity of the multiplet. This last quantity is obtained by multiplying the sum of the intensities of the individual lines observed by the multiplet correction factor, which is defined as

\[
m_{\text{eff}} = \frac{\sum_{\text{all}} s_{ij}}{\sum_{\text{obs}} s_{ij}},
\]

where \( s_{ij} \) is the theoretical line strengths, which are constructed by assuming that they are proportional to the populations of their parent levels, if we assume LTE computation predictions. The upper sum runs over all the lines of the multiplet, and the lower sum runs over the observed lines of the multiplet.

The O\( ^{++} \) and C\( ^{++} \) abundances from RLs have been calculated using the representative \( T_e \)-values of these ions, \( T_e([\mathrm{O \, III}]) \), and the effective recombination coefficients that are available in the literature (Storey [1994]) for O\( \mathrm{II} \), assuming LS coupling, and Davey et al. [2000] for C\( \mathrm{II} \). The O\( ^{++} \) abundance has only been computed when at least three lines of multiplet 1 were measured in a given one-dimensional spectrum. The final number of apertures with determinations of the O\( ^{++}/H^+ \) ratio obtained from RLs was 671, 92% of the total number of available one-dimensional spectra. Non-LTE (NLTE) corrections are not taken into account for deriving the O\( ^{++} \) abundances (see Tasmis et al. [2003]; Ruiz et al. [2003]; Peimbert et al. [2005]), considering (1) that we use several lines of the multiplet and (2) the high densities, between 4000 and 6000 cm\(^{-3} \) (e.g., Esteban et al. 1998, 2004), of the Orion Nebula.

5. SPATIAL PROFILES ALONG THE SLIT POSITIONS

5.1. Physical Conditions

The first step in the analysis of our results was the obtaining of spatial profiles of several nebular parameters along the slit positions. The selected parameters were \( \epsilon(H\beta) \), \( n_e \), \( T_e([\mathrm{O \, III}]) \), \( T_e([\mathrm{O \, II}]) \), the intensity of several selected lines (H\( \beta \), C\( \mathrm{II} \) \( \lambda \lambda 2467, \lambda \lambda 24649, [\mathrm{O \, II}] \lambda \lambda 4579, [\mathrm{Fe \, III}] \lambda \lambda 4881, [\mathrm{N \, II}] \lambda \lambda 5755 and 5768, [\mathrm{O \, I}] \lambda \lambda 6300, and [\mathrm{S \, II}] \lambda \lambda 6717 and 6731), the O\( ^{++}/H^+ \) ratio obtained from CELs and RLs, and the C\( ^{++}/H^+ \) ratio obtained from RLs. In Figures 4–8 we show some selected spatial profiles of slit positions 3, 6, 1, 4, and 5, respectively. Slit positions 3 and 6 are the most interesting ones, and we will focus our discussion on their main features. Slit position 3 crosses the Orion bar and the Herbig-Haro (HH) objects HH 203 and HH 204, and slit position 6 passes through the brightest part of the nebula at the southwest of the Trapezium cluster and crosses two proplyds, 159–350 and 177–341, as well as HH 530.

The spatial profiles of \( n_e \) show a large range of variation across the slits, with local maxima associated with the positions of proplyds, HH objects, the Orion bar, and the bright zone at the southwest of the Trapezium (see Figs. 4a–8a). The highest densities are found at the proplyd 159–350, which has been observed in slit positions 5 and 6 (see Figs. 8a and 5a, respectively). This object shows \( n_e \)-values on the order of \( 6 \times 10^4 \) and \( 2 \times 10^4 \) cm\(^{-3} \) in slit positions 5 and 6, respectively, whereas the proplyd 158–326, which is near \( \theta^1 \) Ori C, shows values somewhat larger than \( 4 \times 10^4 \) cm\(^{-3} \) (see Fig. 6a). The densities at the brightest zone of the nebula, at the southwest of the Trapezium, are about 2.5 \( \times 10^4 \) cm\(^{-3} \) (see Fig. 5a). It is obvious that such high \( n_e \) determinations based on the [S\( \mathrm{II} \)] doublet are not totally confident, because they are at the high-density limit of this indicator. The HH objects are also associated with local peaks of \( n_e \), but not as high as those for the proplyds; in fact, HH 202, HH 203, and HH 204 show maxima of between 6000 and \( 1 \times 10^4 \) cm\(^{-3} \). In Figure 4a, the dashed line marks the \( n_e \)-value obtained from the whole-slit (integrated) spectrum, 2460 cm\(^{-3} \), whereas the minimum and maximum values are about 700 and 8000 cm\(^{-3} \), covering a range of 1 order of magnitude. In Figure 5a, we can see that the range of variation of \( n_e \) is also dramatic along slit position 6. In this figure we also compare the values corresponding to the whole-slit spectrum, 5500 cm\(^{-3} \), and the background-gas spectrum, 4700 cm\(^{-3} \), which corresponds to an integrated spectrum excluding the emission of the proplyds. As we can see, the measured density increases by 800 cm\(^{-3} \), about 17%, when we include the emission of the proplyds in the integrated spectrum of the slit.

The spatial profiles of \( T_e([\mathrm{N \, II}]) \) and \( T_e([\mathrm{O \, III}]) \) show very interesting features (see Figs. 4b–8b). The proplyds observed in slit positions 1, 5, and 6 show quite prominent spikes of \( T_e([\mathrm{O \, III}]) \) and less or almost absent ones of \( T_e([\mathrm{O \, II}]) \). In slit position 6 (Fig. 5b), the value of \( T_e([\mathrm{O \, III}]) \) increases locally by about 70% at the location of proplyd 177–341, and a similar spike shows the location of proplyd 179–337 in slit position 5 (Fig. 8b). The value of \( T_e([\mathrm{N \, II}]) \) is also higher than the mean by 50% and 40% at the position of proplyd 159–250 in slit positions 5 and 6, respectively. For all the proplyds, the increase of \( T_e([\mathrm{O \, III}]) \) is only of a few hundred kelvins at most. In Figure 5b, we can also see a relatively broad, about 500-km\(^{-1} \), spike of \( T_e([\mathrm{N \, II}]) \) at 130°, where the temperature increases by about 15%. This feature is not related to any local structure reported by Bally et al. (2000), but rather with a conspicuous dark globule that can be seen at the edge of the bright zone at the southwest of the Trapezium. There are also less important temperature spikes related to some HH objects. In Figure 4b, we can see that the value of \( T_e([\mathrm{N \, II}]) \) increases by about 15% at the location of HH 204, and that the increase is slightly lower for the case of HH 203. In contrast, HH 203 does not show that behavior, and its temperatures are similar to those of the surrounding gas. In HH 202 (seen in slit position 4), the increase of the values of \( T_e([\mathrm{N \, II}]) \) and \( T_e([\mathrm{O \, III}]) \) are only about 8% and 5%, respectively (Fig. 7b). The other HH objects that we have observed, HH 529 and HH 530, do not show temperature variations with respect to the surrounding gas (Figs. 6b and 5b). The different behavior of the temperatures in the HH objects does not seem to be correlated with the velocity of their associated flows as reported by Henney et al. (2007). There is a final interesting feature regarding the temperature profiles that can be seen in Figure 4b. Although \( T_e([\mathrm{N \, II}]) \) is almost always a few hundred kelvins larger than \( T_e([\mathrm{O \, II}]) \) in all the slit positions (this has been also observed in previous works; e.g., Baldwin et al. 1991; Rubin et al. 2003), the zone around the Orion bar, between 130° and 150° in Figure 4b, shows a reversal of this relation in just the inner 10° of the bar. In contrast, \( T_e([\mathrm{N \, II}]) \) shows a local increase just outside the bar. This local increment of \( T_e([\mathrm{O \, III}]) \) that we see in this particular zone could be related to the highly ionized jet, which is especially bright in \( [\mathrm{O \, III}] \), that leads to HH 203 and HH 204 (see Doi et al. 2004). In fact, the position of this zone coincides with a knot of high–[O\( \mathrm{III} \)] emission, which
The horizontal dashed line gives the average value of \( n_e \) for the whole-slit (integrated) spectrum. (c) Top: Profiles of \( T_e([\text{O} \text{ iii}] ) \) (dash-dotted line) and \( T_e([\text{N} \text{ ii}] ) \) (solid line). The horizontal solid and dashed lines represent the values of this ratio for the background-gas and whole-slit spectra, respectively. (c) Profile of \( \frac{F(\text{Fe} \text{ ii})}{F(\text{O} \text{ ii})} \) (solid line) and \( \frac{F(\text{O} \text{ ii})}{F(\text{O} \text{ i})} \) (dash-dotted line). Bottom: Profile of the \( \frac{F(\text{Fe} \text{ ii})}{F(\text{O} \text{ ii})} \) ratio. The vertical gray bands indicate zones without a reliable measurement of the \( \frac{F(\text{O} \text{ ii})}{F(\text{O} \text{ i})} \) ratio. The horizontal solid and dashed lines represent the values of the ADF for the background-gas and whole-slit spectra, respectively, and the vertical gray bands indicate zones without a reliable determination of the \( \frac{F(\text{O} \text{ ii})}{F(\text{O} \text{ i})} \) ratio from RLs.

Rubin et al. (2003) obtained HST STIS spectroscopy of a slit position very similar to our position 3—their slit 4—and show its \( T_e([\text{O} \text{ iii}] ) \) spatial profile in their Figure 3a. If we compare that figure with our Figure 4b, we can see that the point-to-point dispersion of the temperature is substantially lower in our data. In fact, whereas \( T_e([\text{O} \text{ iii}] ) \) varies from 6500 to 12,000 K in slit 4 of Rubin et al. (2003), the variations are only from 8000 to 9000 K in our slit position 3. This fact has two possible explanations: (1) the presence of real temperature variations with a typical spatial scale of between 0.5\( \alpha \) (the spatial resolution of the Rubin et al. data) and 1.2\( \alpha \) (our resolution) in the plane of the sky, or (2) that the temperature variations reported by Rubin et al. (2003) are spurious and are produced by the much lower signal-to-noise ratio of their data. We think that the second explanation is perhaps the most likely one, considering that the deepest exposures obtained by Rubin et al. for the spectral range containing \([\text{O} \text{ ii}] \) \( \lambda \lambda 4363 \) were about 1060 s long, and our exposures were between 1800 and 2200 s long. Moreover, an important factor should be added to correct for the different apertures of the telescopes used in this work and in Rubin et al. (4.2 and 2.4 m, respectively), as well as for the smallest element of spatial resolution used in Rubin et al.'s observations.

It is clear that the behavior of \( T_e([\text{N} \text{ ii}] ) \) and \( T_e([\text{O} \text{ iii}] ) \) at the positions of proplyds and HH objects is different. In Figures 4b–8b we also include the ratio of both temperatures, which shows clearly that the increase of \( T_e([\text{N} \text{ ii}] ) \) is greater than that of \( T_e([\text{O} \text{ iii}] ) \) in proplyds. The presence of \( T_e([\text{N} \text{ ii}] ) \) enhancements in the proplyds of the Orion Nebula was previously reported by Rubin et al. (2003), and they interpret this as the effect of collisional deexcitation on the nebular lines of \([\text{N} \text{ ii}] \) due to the high densities of these objects. We have explored that possibility, comparing the spatial profile of the intensity of the \([\text{N} \text{ ii}] \) \( \lambda \lambda 5755 \) and \( \lambda 6584 \) lines. Both lines come from upper levels, but with very different critical densities: 7.9 \( \times \) 10\( ^6 \) cm\(^{-3} \) in the case of the \([\text{N} \text{ ii}] \) \( \lambda 5755 \) line, and 5.8 \( \times \) 10\( ^4 \) cm\(^{-3} \) in the case of the \([\text{N} \text{ ii}] \) \( \lambda 6584 \) line. In Figures 5c and 6c, we can see that the two proplyds with the largest electron densities (\( n_e > 2 \times 6 \times 10^4 \) cm\(^{-3} \)), 159–350 (also observed in Fig. 8c) and 158–323, show a spike in the brightness of the \([\text{N} \text{ ii}] \) \( \lambda 5755 \) line, whereas the \([\text{N} \text{ ii}] \) \( \lambda 6584 \) line does not show such a clear increase in its brightness with respect to the emission of the surroundings. However, the proplyds with the lowest electron densities (\( n_e < 1 \times 10^4 \) cm\(^{-3} \)), 177–341 and 170–337 (Figs. 5c...
and 8c), show similar localized enhancements of the intensity of both [N ii] lines, indicating that collisional deexcitation seems to be not so important in these two proplyds.

In order to further explore whether the different behavior of the auroral and nebular $T_e([\text{N} \, \text{ii}])$ lines in some proplyds is due to collisional deexcitation, we have constructed Figure 9. In this figure, we show the theoretical curves of the $n_e$ and $T_e$ pairs that reproduce the observed range of values of the $\text{[N ii]}$ 5755/6584 line ratio in the proplyds, as well as the line of the lower limit of $n_e$, which corresponds to the lowest value of the $[\text{S ii}]$ 6731/6717 ratio measured in these objects. The theoretical predictions have been constructed with emissivities calculated by the photoionization code PHOTO as described in Stasińska (2005), kindly provided by G. Stasińska (2007, private communication).

Unfortunately, the results of Figure 9 are not conclusive, but considering that the estimated $n_e$-value of the proplyds should be a lower limit of the true one, the permitted area of the diagram indicates that collisional deexcitation should be acting. Moreover, if that is correct, the true electron temperature should be lower than that actually indicated by $T_e([\text{N} \, \text{ii}])$, but perhaps not too different from the values corresponding to the surrounding ionized gas (which are never lower than 3000 K). It is important to note that the $T_e([\text{N} \, \text{ii}])$-values that we obtain for the whole-slit and the background-gas spectra of positions 5 and 6 only show differences on the order of a few tens of kelvins. This indicates that the contribution of proplyds in the integrated spectrum does not produce a substantial increase of the derived electron temperature. On the other hand, in contrast with what happens in proplyds, the increase of $T_e([\text{N} \, \text{ii}])$ that we see in the HH objects does not seem to be related to collisional deexcitation. This is suggested because the HH objects show lower values of $n_e$ and lower $T_e([\text{N} \, \text{ii}])$ peaks than those of the proplyds, because their values of $T_e([\text{N} \, \text{ii}])$ and $T_e([\text{O} \, \text{iii}])$ show similar enhancements (see Figs. 4b and 7b), and because of the spatial coincidence of conspicuous similar peaks in both the $[\text{N} \, \text{ii}]$ 5755 and 6584 lines. Therefore, the $[\text{N} \, \text{ii}]$ emission of the HH objects should not be affected by substantial collisional deexcitation, and their electron temperature is higher, probably because the action of an additional source of heating, perhaps related to shock excitation.

5.2. Line Fluxes

One of the main spectral properties of HH objects is their strong emission in $[\text{Fe} \, \text{iii}]$ lines. In Figure 4c, we can see the spatial profile of the $F([\text{Fe} \, \text{iii}] 4681)/F(\text{H} \beta)$ line ratio along slit position 3. For HH 204, the intensity of that line is a factor of 5 brighter than that for the Orion bar. This object also shows a similar enhancement.
in the [O i] 6300 line, as well as more moderate ones in the [S ii] and [N ii] lines. In the case of HH 202, observed in slit position 4, the intensity of the [Fe iii] λ4881 line increases by a factor of 10 (Fig. 7c). The rest of the HH objects observed, HH 204, HH 529, and HH 530, also show enhancements in the [Fe iii], [O i], [N ii], and [S ii] lines. These are common spectral features in shock-excited objects (see Hartigan et al. 1987). In contrast, the proplyds show [O i] spikes of moderate intensity and reversed spikes in the [S ii] λ6717 and λ6731 lines, perhaps also due to collisional deexcitation because of the rather low critical densities of the upper levels of those [S ii] transitions. The [O i] emission emerges from the photodissociation of OH in the H/H₂ front that lies close to the protoplanetary disk surface (Storzer & Hollenbach 1998).

In Figures 4d–8d, we show the spatial profiles of the pure RLs of C ii λ4267 and O ii λ4649 along the slit positions. The spatial distributions of the C ii and O ii lines are very similar. However, in the cases of the slit positions passing through the center, especially in positions 1 and 6, there is a slight decrease of the C ii/O ii ratio toward the central parts of the nebula. This variation could be due to the increase of the C³⁺ ionization fraction near the Trapezium stars.

In Figures 4e–8e, we show the spatial profiles of the O ii λ4649 and [O ii] λ4959 lines, which show a fairly similar spatial distribution in all the slit positions. This behavior is very different to that observed in PNs (Liu et al. 2000; Garnett & Dinerstein 2001; Krabbe & Copetti 2006), where the O ii line emission peaks closer to the central star than does the [O iii] line. We only find some localized enhancements of the [O iii]/O ii ratio, which are related to the positions of some proplyds (see Figs. 5e and 8e). These enhancements of the [O iii]/O ii ratio are correlated with the increase of the continuum due to the emission of proplyds that show a large number of absorption features that produce a decrease in the intensity of the O ii λ4649 line (see § 5.3).

5.3. The Abundance Discrepancy Factor

Finally, Figures 4f–8f show the spatial variation of the O⁺⁺/H⁺ ratios obtained from CELs and RLs, as well as the AD factor (ADF), which is defined as

$$ADF(O^{++}) = \log(O^{++}/H^+)_{RLs} - \log(O^{++}/H^+)_{CELs}$$

for all the slit positions. The most interesting result concerning these figures is that the ADF remains fairly constant along most of the observed zones of the nebula, showing values between 0.15 and 0.20 dex, in agreement with the determinations by Esteban et al. (1998, 2004) that were based on deep echelle spectrophotometry of selected small areas of the Orion Nebula. It is necessary to note that the behavior of the ADF close to the proplyds is not confidently determined, because the O ii lines are not properly measured in most of these objects due to the aforementioned strong increase of the continuum, which makes it difficult to measure of weak lines and the effects of possible absorption features of their spectra. In any case, Figure 5f shows a quite convincing
decrease of about 0.10 dex in the O/\textsuperscript{++}/H\textsuperscript{+} ratios obtained from CELs at the location of proplyd 177/\textsuperscript{C0} 341.

Another remarkable feature of the ADF along the slits can also be seen in Figure 5\textsuperscript{f}, where we find a slightly higher ADF in an area between proplyds 159/\textsuperscript{C0} 350 and 177/\textsuperscript{C0} 341. It is interesting to note that slit position 5 (Fig. 8\textsuperscript{f}) also shows the same higher values of the ADF between proplyd 159/\textsuperscript{C0} 350 and the area just at the north of proplyd 177/\textsuperscript{C0} 341. This common behavior in both slit positions indicates that the local increase of the ADF should be real. This enigmatic zone of relatively high values of the ADF has an apparent diameter of about 30\textsuperscript{00} and is located about 23\textsuperscript{00} south of the star \textsuperscript{0} Ori C. There is no apparent morphological and/or kinematical feature related to this zone.

In Figures 5\textsuperscript{f}–8\textsuperscript{f}, we also include the values of the ADF that correspond to the whole-slit and background-gas spectra. It can be seen that the ADF of the background-gas spectrum is consistent with the average value of the different individual apertures extracted from the slit positions. However, the ADF obtained for the whole-slit spectrum, which is almost coincident with that of the background-gas spectrum in slit positions 1, 3, and 4, is substantially lower, about 0.1 dex, in slit positions 6 and 5 (Figs. 5\textsuperscript{f} and 8\textsuperscript{f}, respectively). The reason for this surprising result is most probably related to the strong contribution of the proplyds to the continuum of the integrated spectra, and that this contribution is producing some absorption in the O/\textsuperscript{ii} lines at HH 203, HH 204, and HH 202. The large increase of the ADF is due to the low values of the O/\textsuperscript{++}/H\textsuperscript{+} ratios determined by CELs in these zones. In contrast, the O/\textsuperscript{++} abundances determined by RLs do not show such a strong localized decrease. It is interesting to compare the behavior of the ADF at the HH objects and at the Orion bar in Figure 4. At the bar, we can see a similar decrease of the O/\textsuperscript{++}/H\textsuperscript{+} ratios determined from both kinds of lines, but which produce an ADF similar to the mean value along the slit. As has been discussed above, collisional deexcitation does not seem to affect the intensity of the nebular [N/\textsuperscript{ii}] lines at HH 203 and HH 204, and therefore, if we consider the larger critical densities of the [O/\textsuperscript{iii}] lines, this effect is even less likely to be producing the observed decrease of the O/\textsuperscript{++}/H\textsuperscript{+} ratios determined from CELs. The observed behavior of the ADF in the HH objects could be explained by the presence of localized heating due to a nonradiative process, most likely shock excitation, that would lead to the derivation of a lower O/\textsuperscript{++}/H\textsuperscript{+} (CELS) ratio, and this seems to be the case for HH 204, which shows a conspicuous spike of T_e([O/\textsuperscript{iii}]) (Fig. 4\textsuperscript{b}). However, this hypothesis fails to reproduce the presence of high ADFs in HH 203 and HH 202, where there are no spikes of T_e([O/\textsuperscript{iii}]). Another explanation could be the presence of a localized high value of r\textsuperscript{2} in those particular zones, but unfortunately, we cannot check this possibility with our data. Finally, the other HH objects that...
are observed, HH 529 and HH 530, do not show any distinguishable enhancement of the ADF.

6. RADIAL DISTRIBUTIONS OF SOME RELEVANT NEBULAR PARAMETERS

We have constructed radial distribution diagrams of several nebular parameters, combining the data of the different slit positions...
and projecting the angular distance of the center of each individual one-dimensional spectrum with respect to $\theta^1$ Ori C (Fig. 11). In these diagrams, we have only included the data of those apertures corresponding to the background gas; i.e., we have excluded all the points associated with proplyds or HH objects. We include the same points in all three panels of Figure 11, and only those for which the ADF was calculated. These diagrams permit us to study possible large-scale variations of the properties of the ionized gas across the nebula.

In Figure 11a, we show the radial distribution of $T_e([O\text{ iii}])$, which shows a slight but clear general decrease with increasing distance from $\theta^1$ Ori C. In this figure, a bump can be seen in the temperature distribution of slit position 3 between 90$''$ and 120$''$. This bump corresponds to the local increase of $T_e([O\text{ iii}])$ that occurs at the inner part of the Orion bar (see also Fig. 4b). We have made a least-squares linear fit to the data shown in Figure 11a, but excluding those points belonging to the Orion bar. The result is

$$T_e([O\text{ iii}]) (K) = 8540 - 3.6r,$$

where $r$ is the distance from $\theta^1$ Ori C in units of arcseconds. The uncertainty of the slope is 0.2 K arcsec$^{-1}$, and the Spearman’s correlation coefficient is 0.63 (hereafter, all the correlation coefficients we use are Spearman’s). Walter et al. (1992) obtained a radial distribution of $T_e([O\text{ iii}])$ with a positive slope of 6.7 K arcsec$^{-1}$ in the northwestern quadrant of the nebula, fitting their own data and others from the literature. The result of these authors disagrees with the clear behavior shown by our data in Figure 11a, which seems to be independent of the location of each slit position and even includes zones of the northwestern quadrant, our slit position 4. On the other hand, O’Dell et al. (2003) do not find significant spatial variations of $T_e([O\text{ iii}])$ across the nebula in their high-resolution map of the $[O\text{ iii}]$ ratio obtained by the WFPC at the HST. As we can see, the different results regarding the large-scale temperature variations in the Orion Nebula are contradictory; however, we consider our data set to be more reliable than the previous ones, as it is based on homogeneous, higher signal-to-noise ratio spectroscopic observations.

In Figure 11b, it is evident that $T_e([N\text{ ii}])$ also shows a radial decrease. The least-squares linear fit to the data gives

$$T_e([N\text{ ii}]) (K) = 9460 - 7.8r.$$

We can see that the slope of the fit is larger than that obtained for $T_e([O\text{ iii}])$, and in this case, the result agrees qualitatively with the temperature gradient obtained by Walter et al. (1992) from the $[N\text{ ii}]$ lines ($-17.1$ K arcsec$^{-1}$) in the inner 170$''$ of the nebula. The uncertainty of the slope of our fit is 0.6 K arcsec$^{-1}$, and its correlation coefficient is 0.52. Sánchez et al. (2007) obtain a bi-dimensional map of the spatial distribution of $T_e([N\text{ ii}])$, and they...
also find that this parameter is higher near the Trapezium stars and drops toward the outer zones of the nebula, in qualitative agreement with our result.

Finally, in Figure 11c, we show the radial distribution of the ADF(O++) across the nebula. In this figure, part of the relatively large dispersion is due to the large observational uncertainty in several apertures. In fact, most of the data points with the highest and lowest values of the ADF correspond to low signal-to-noise ratio determinations at the edges of slit positions 1, 4, and 5. Despite the dispersion being relatively large, the first visual impression suggests that the ADF is rather constant or very slightly decreasing toward the outer parts of the nebula. In fact, the least-squares linear fit of all the points gives

$$ADF(O^{++}) = 0.2050 - 0.0005r,$$  \hspace{1cm} (6)

but with a very low correlation coefficient (0.32). However, other possibilities of fitting are possible. A more detailed inspection of Figure 11c shows that the ADF seems to increase toward the center, in the innermost 40\" of the nebula, and that this parameter becomes basically constant for larger distances (the inner points of slit positions 1 and 5 consistently suggest the same tendency). We have divided the least-squares linear fit to the ADF into two regions, the first for the points in the inner 40\", and the second for the points outside this area, for which we have assumed a zero slope. The fits are the following:

$$ADF(O^{++}) = 0.279 - 0.003r \quad (r \leq 40\"),$$ \hspace{1cm} (7)

with a correlation coefficient of 0.58, and

$$ADF(O^{++}) = 0.163 \quad (r > 40\") \quad \hspace{1cm} (8)$$

This apparent increase of the ADF toward the inner zones of the nebula can be ultimately related to two other tendencies that we have found in our data: first, the clear correlation illustrated in Figure 11a, which shows that $T_e([O iii])$ is higher in the zones near the Trapezium stars; and second, the possible weak correlation between the ADF and $T_e([O iii])$ that will be discussed in § 7. Therefore, the ADF seems to increase very slightly in the inner and systematically hotter zones of the nebula. If this behavior is real, it would indicate that whatever process is producing the ADF increases somehow with the local ionization of the gas, or that it depends on the distance between 6\° Ori C and the ionization front, from which most of the nebular emission comes. This last possibility arises because, due to the blister geometry of the Orion Nebula, the smaller distance of the Trapezium stars to the main ionization front occurs precisely behind that massive star cluster (see Wen & O’Dell 1995).

7. CORRELATIONS BETWEEN THE ADF AND OTHER NEBULAR PROPERTIES

In order to shed some light on the physical nature of the ADF problem, we have explored the relationship of this parameter with other nebular properties determined from our one-dimensional spectra. Figure 12 illustrates the dependence of the ADF(O++)...
with respect to c(Hβ) (Fig. 12a), $n_e$ (Fig. 12b), $T_e([\text{O} \text{ iii}]/([\text{O} \text{ ii}]))$ (Fig. 12c), the $T_e([\text{N} \text{ ii}])/T_e([\text{O} \text{ iii}])$ ratio (Fig. 12d), the O$^{++}$/O ratio determined from CELs (Fig. 12e), and the mean-square electron temperature fluctuation, $r^2$, which can be parameterized in terms of the average temperature, $T_0$, and the mean-square electron temperature fluctuation, $r^2$, which are defined as

$$T_0 = \frac{\int T_e n_e n_i \, dV}{\int n_e n_i \, dV},$$

$$r^2 = \frac{\left( T_e - T_0 \right)^2 n_e n_i \, dV}{\int n_e n_i \, dV},$$

where $n_i$ is the ion density. The integrations are calculated over the entire volume, and the element of volume, $dV$, can be expressed as $dl \, dA$, the product of the elements of the length of the column along the line of sight and the surface area in the plane of the sky, respectively. Our spatially resolved spectroscopic data do not permit us to obtain a direct determination of $r^2$ along the line of sight. However, a discrete estimation of $r^2$ in the plane of the sky, $r^2$, can be obtained through the point-to-point determinations of $T_e$ that we have obtained from the individual one-dimensional spectra extracted along the slit positions. Following a similar procedure as Liu (1998), Rubin et al. (2003), and Krabbe & Copetti (2005), and assuming that $n_e \approx n(\text{H}^+) \approx 10^4$ cm$^{-3}$ in all the points of the nebula, we can compute $T_{0,A}$ and $r^2_A$ using the following equations:

$$T_{0,A} = \frac{\sum_j T_{e,j} n_{e,j}^2 [n(\text{X}^{+j})/n(\text{H}^+)])_j}{\sum_j n_{e,j}^2 [n(\text{X}^{+j})/n(\text{H}^+)])_j},$$

$$r^2_A = \frac{\sum_j (T_{e,j} - T_{0,A})^2 n_{e,j} [n(\text{X}^{+j})/n(\text{H}^+)])_j}{T_{0,A} \sum_j n_{e,j} [n(\text{X}^{+j})/n(\text{H}^+)])_j},$$

where $T_{e,j}$, $n_{e,j}$, and $[n(\text{X}^{+j})/n(\text{H}^+)])_j$ are the electron temperature, the electron density, and the ionic abundance of the X$^{++}$th species in the jth aperture extracted from a given slit position. The quantity $T_{e,j}$ used in the equations above corresponds to the average temperatures along the line of sight that crosses the nebula at the jth aperture, and it can be expressed as

$$T_{e,j} = \frac{\int T_e n_e n_i \, dl}{\int n_e n_i \, dl}.$$

If we take this into account, it is likely that the value of $r^2_A$ that we obtain is substantially lower than $r^2$, and, more strictly speaking, it should be considered a lower limit to $r^2$ (see further argumentation given by Rubin et al. [2003] and O’Dell et al. [2003]). In Table 4, we summarize the values of $r^2_A$ that we obtain for each slit position and for each of the two ions for which we have determinations of $T_e$. We have included all the points for which $T_e$ has been determined in the sums, even those belonging to proplyds or HH objects, in order to explore the effect of these structures into the derivation of $r^2$. Part of the value of $r^2_A$ that we calculate for each ion comes from errors in the measurement of the emission-line ratios, so the intrinsic value of $r^2_A$ must be corrected by the relative mean quadratic error of the $T_e$ measurements, $r^2_{A, \text{err}}$, with the simple relation $r^2_A = r^2_{A, \text{err}}$ (see O’Dell et al. 2003; Krabbe & Copetti 2005). The values of $r^2$ for each ion and slit position are also included in Table 4, and they are always lower than the corresponding values of $r^2_A$, except in the case of slit position 3, where the errors are slightly higher, indicating that most of the temperature variation along slit position 3 is produced by measurement uncertainties. The corrected value of $r^2_A$ that we obtain is very low in all cases: $r^2_A(\text{O}^{++})$ ranges from $\approx 0$ to 0.0011, and $r^2_A(\text{N}^+)\approx 0$ to 0.0112. However, Rubin et al. (2003)



8. TEMPERATURE FLUCTUATIONS

Following the formulation proposed by Peimbert (1967), the temperature fluctuation over the observed volume of a nebula

| Slit Position | $r^2_A(\text{O}^{++})$ | $r^2_A(\text{O}^{+++})$ | $r^2_A(\text{H}^+)$ | $r^2_A(\text{H}^+)$ | $r^2_A(\text{O}^{++})$ |
|---------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1             | 0.0011          | 0.0002          | 0.0127          | 0.0015          | 0.028           |
| 3             | 0.0004          | 0.0006          | 0.0010          | 0.0011          | 0.038           |
| 4             | 0.0008          | 0.0003          | 0.0055          | 0.0016          | 0.029           |
| 5             | 0.0004          | 0.0002          | 0.0015          | 0.0019          | 0.025           |
| 6             | 0.0005          | 0.0002          | 0.0024          | 0.0017          | 0.025           |
obtain $t_2'(O^{+\dagger}) = 0.0068 - 0.0176$ and $t_2'(N^\dagger) = 0.0058 - 0.0175$ for the different slit positions they observe in the Orion Nebula, values that are relatively consistent with ours in the case of $t_2'(N^\dagger)$ but are considerably larger in the case of $t_2'(O^{+\dagger})$. On the other hand, O'Dell et al. (2003) obtain $t_2'(O^{+\dagger}) = 0.0050 - 0.0156$, which are values in good agreement with those obtained by Rubin et al. (2003), but also much higher than our determinations. The reason of this discrepancy is difficult to ascertain. The resolution element of each set of observations is rather different; our apertures are $1.2'' \times 1.03''$, and those of Rubin et al. (2003) and O'Dell et al. (2003) are $0.5'' \times 0.5''$ and $0.1'' \times 0.1''$, respectively. If the spatial resolution has something to do with the different values of $t_2'(O^{+\dagger})$ obtained in this work and the previous works, this would imply that the small-scale spatial variations of $T_e([O \ \text{iii}])$ have a characteristic size of between $0.5''$ and $1.0''$ and that those related to $T_e([N \ \text{ii}])$ are larger: at least on the order of the size of our apertures. In any case, this seems to us to be a rather unlikely scenario. Another difference between our determinations and those of Rubin et al. (2003) and O'Dell et al. (2003) is that those authors use a relation for determining $T_e$ from the [O ii] line ratio that is valid in the low-density limit, while our calculations are based on solving the statistical equilibrium equations for the value of $n_e$ measured for each particular aperture. We have explored the effect of this different procedure by applying equation (5) of Rubin et al. (2003), which was also used by O'Dell et al. (2003), to our data of slit position 6. In Figure 13, we show the ratio of the values of $T_e([O \ \text{iii}])$ computed using the low-density limit approximation equation and our own determinations, and we find a systematical bias of about 1.12 and a small bump (~5%) that is coincident with the zone of the highest density at the southwest of the Trapezium (see Fig. 5a). The use of both different procedures does not substantially increase the $T_e$ dispersion. In fact, using the low-density limit approximation, we obtain $t_2'(O^{+\dagger}) = 0.0008$ for slit position 6, which is only 60% larger than our calculations. Therefore, the use of a low-density limit approximation does not explain the large differences of $t_2'(O^{+\dagger})$ that are found between our results and those of the other authors. A final possibility is the different signal-to-noise ratios of the data sets that we are comparing. As was mentioned in § 5.1, this is a likely source of discrepancies in the case of the long-slit data of Rubin et al. (2003), but this is more difficult to ascertain in the case of the data of O'Dell et al. (2003). These authors estimate a representative probable error of about 4.2% for their point-to-point $T_e([O \ \text{iii}])$ determinations, which corresponds to a value of $t_2'_{\text{err}}$ of about 0.0017, which is larger than our observational errors, but much lower than their nominal values of $t_2'(O^{+\dagger})$, indicating that the temperature variations obtained by O'Dell et al. (2003) should be real if the errors are not largely underestimated. Only observations combining a very high signal-to-noise ratio and very high spatial resolution will be able to solve this puzzle.

As has been stated before, our spatially resolved spectroscopic data do not permit us to determine the value of $t^2$ along the line of sight, which we denote as $t^2_3$, but an indirect estimate can be obtained if we assume that the ADF is produced by the presence of such temperature variations. Although this is still a controversial possibility, there are some pieces of evidence that indicate that this may be correct, at least in the case of H ii regions (see Garcia-Rojas & Esteban 2007). O'Dell et al. (2003) show that the relation between $t^2_3$, $t^2_2$, and the total $t^2$ in three dimensions is

$$t^2 = t^2_3 + \langle t^2_2 \rangle,$$

where $\langle t^2_2 \rangle$ is the average over all lines of sight. In Table 4, we include the values of $\langle t^2_2(O^{+\dagger}) \rangle$ that we obtain for each slit position. These values have been estimated from the average ADF($O^{+\dagger}$) of the individual apertures of each slit position. From the table, it can be seen that the values of $\langle t^2_2(O^{+\dagger}) \rangle$ are rather similar for the different slit positions and are consistent with previous determinations, between 0.018 and 0.028 (Esteban et al. 1998, 2004), except in the case of slit position 3, which shows a rather higher value. This large temperature fluctuation comes from the also larger ADFs that we obtain at HH 203 and HH 204 (see Fig. 4f). If we take into account that the values of $t^2_2(O^{+\dagger})$ are much lower than the values of $\langle t^2_2(O^{+\dagger}) \rangle$, we may make the approximation that $t^2(O^{+\dagger}) \approx \langle t^2_2(O^{+\dagger}) \rangle$. To follow the arguments of O'Dell et al. (2003), this result would indicate that the hypothetical thermal inhomogeneities producing $t^2$ should be small-scale ones and unresolved by our data; i.e., smaller than our spatial resolution limit of about 1''. On the other hand, our spatial resolution is unable to resolve the size of $10^{13} - 10^{14}$ cm that Stasińska et al. (2007) derive for the metal-rich drops they claim to be the most likely explanation of the AD.

9. CONCLUSIONS

We have studied the spatial distribution of a large number of nebular quantities along five slit positions covering different morphological zones of the Orion Nebula. The resolution element of the observations was $1.2'' \times 1.03''$. The studied quantities were $c(H/\beta)$, $n_e$, $T_e([N \ \text{ii}])$, $T_e([O \ \text{iii}])$, the intensity of several selected lines (H/\beta, C ii $\lambda 4267$, O ii $\lambda 4649$, [O iii] $\lambda 4959$, [Fe iii] $\lambda 4881$, [N ii] $\lambda 5875$ and $\lambda 6584$, [O i] $\lambda 6300$, and [S ii] $\lambda 6717$ and $\lambda 6731$), the O''/H'' ratio obtained from collisionally excited lines (CELs) and recombination lines (RLs), and the C''+/H'' ratio obtained from RLs. The total number of apertures or one-dimensional spectra extracted was 730. We have been able to determine the O''/H'' ratio from the faint RLs of this ion in 92% of the aperture areas.

The spatial distribution of $n_e$ shows a large range of variation, larger than an order of magnitude, across the nebula, with local maxima associated with the positions of protoplanetary disks (proplyds), Herbig-Haro objects, the Orion bar, and the brightest area of the nebula at the southwest of the Trapezium. The proplyds show quite prominent spikes of $T_e([N \ \text{ii}])$ and much lesser ones of $T_e([O \ \text{iii}])$. This could be due to collisional deexcitation on the nebular lines of [N ii] because of the high densities of these
objects. The Herbig-Haro objects also show somewhat higher values of $T_e([\text{N} \, II])$, but in this case, the origin could be related to extra heating of the gas due to shock excitation. The spatial distribution of the O $\lambda$4994 and [O $\lambda$] $\lambda$4959 lines is fairly similar along all the slit positions: a very different behavior from that observed in planetary nebulae. We have found that the abundance discrepancy factor (ADF) of O$^{++}$, which is the difference between the O$^{++}$ abundance determined from RLs and that from CELs, remains, in general, rather constant along most of the observed areas of the nebula, showing values of between 0.15 and 0.20 dex. However, there are some localized enhancements of the ADF, especially at the position of the Herbig-Haro objects HH 202, HH 203, and HH 204.

The combined data of all slit positions indicate a clear decrease of $T_e([\text{N} \, II])$ and $T_e([\text{O} \, III])$ with increasing distance from the main ionizing source of the nebula, $\theta^1$ Ori C. On the other hand, the radial distribution of the ADF shows a rather constant value across the nebula, except at the inner 40$, where the ADF seems to increase very slightly toward $\theta^1$ Ori C.

We have explored possible correlations between the ADF of O$^{++}$ and other nebular quantities, and we find a possible very weak increase of the ADF for higher electron temperatures. There are no apparent trends between the ADF and $\epsilon$(H$\beta$), $n_e$, $T_e([\text{N} \, II])$/ $T_e([\text{O} \, III])$, the O$^{++}$ abundance, or the O$^{++}$/O$^+$ ratio.

Our spatially resolved spectroscopy allows us to estimate the value of the mean-square electron temperature fluctuation in the plane of the sky, which is a lower limit to the traditional $r^2$ parameter. We find very low values in all cases, a result that is in contradiction with previous estimates from the literature. Our results indicate that the hypothetical thermal inhomogeneities, if they exist, should be lower than our spatial resolution limit of about 1$''$.

It is clear that further studies on the $T_e$, chemical abundances, and ADF distributions at subarcsecond spatial scales are necessary in trying to disentangle (1) whether small spatial scale temperature fluctuations and/or metal-rich droplets are really present in the Orion Nebula in particular and H $\alpha$ regions in general and (2) the origin of the AD problem and its possible relation to $r^2$ and other nebular properties. The observations needed for this task are very difficult even for ground-based large-aperture telescopes and, at this time, are unfeasible with the current space telescopes and their available instrumentation.

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