SULFUR ABUNDANCES IN THE ORION ASSOCIATION B STARS

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ABSTRACT

Sulfur abundances are derived for a sample of 10 B main-sequence star members of the Orion association. The analysis is based on LTE plane-parallel model atmospheres and non-LTE line formation theory by means of a self-consistent spectrum synthesis analysis of lines from two ionization states of sulfur, S ii and S iii. The observations are high-resolution spectra obtained with the ARCES spectrograph at the Apache Point Observatory. The abundance distribution obtained for the Orion targets is homogeneous within the expected errors in the analysis: \( A(S) = 7.15 \pm 0.05 \). This average abundance result is in agreement with the recommended solar value (both from modeling of the photospheres in one-dimensional and three-dimensional, and meteorites) and indicates that little, if any, chemical evolution of sulfur has taken place in the last ~4.5 billion years. The sulfur abundances of the young stars in Orion are found to agree well with results for the Orion Nebulae, and place strong constraints on the amount of sulfur depletion onto grains as being very modest or non-existent. The sulfur abundances for Orion are consistent with other measurements at a similar galactocentric radius: combined with previous results for other OB-type stars produce a relatively shallow sulfur abundance gradient with a slope of \(-0.037 \pm 0.012\) dex kpc\(^{-1}\).

Key words: open clusters and associations: individual (Ori OB1) – stars: abundances – stars: early-type

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1. INTRODUCTION

The chemical element sulfur, together with O, Ne, Mg, Si, Ar, and Ca, belongs to the family of the so-called α-capture elements, which are light elements with even Z in the range between 6 < Z < 22. Sulfur is among the 10 most abundant elements in the universe and its production occurs both during hydrostatic and explosive oxygen-burning phases in massive star evolution and supernovae of Type II (SN II; Clayton 2003). Although some contribution from SN ii’s is also expected (François et al. 2004, and references therein).

The observed evolution of the sulfur abundance in the Galaxy is generally less well defined than that of other α-elements (such as oxygen or calcium). The earliest determinations of sulfur abundances in stars date from 1980s (Clegg et al. 1981; François 1987, 1988). More recently, Chen et al. (2002) studied S i lines in a sample of disk stars (with [Fe/H] > −1.0) and found that sulfur abundances correlate with those of silicon, as generally expected since these are both considered to be α-elements. Concerning the behavior of [S/Fe] versus [Fe/H] in low-metallicity halo stars, Israelian & Rebolo (2004) and Takada-Hidai et al. (2002) found that [S/Fe] increased linearly with decreasing [Fe/H], while Ryde & Lambert (2004) and Nissen et al. (2004) obtained values of [S/Fe] that are roughly constant and enhanced relative to solar value for metal poor stars, following the general trend observed for other α-capture elements. Caffau et al. (2005), on the other hand, found at low metallicities both a population of stars having a flat [S/Fe] ~ +0.4 dex, and stars with higher [S/Fe] ratios. The recent results by Nissen et al. (2007), which take into account corrections for non-LTE (NLTE) effects, indicate that halo stars follow a plateau at [S/Fe] ~ +0.2 dex.

An important property of sulfur, a volatile element, is that given its low condensation temperature it is not expected to be locked-up significantly into grains, at least not in the low-density interstellar medium, nor in certain nebular sites (Goicoechea et al. 2006). Thus, a comparison between nebular and stellar sulfur abundances may involve relatively small corrections for grain depletion; if true, sulfur then would provide a direct connection between the stellar and gas-phase abundances in the interstellar medium, as well as nebular abundances in galactic and extragalactic environments. This work will focus on defining the present-day stellar sulfur abundance in a sample of young B-star members of the Orion association. These abundances can be used to help define the present-day sulfur abundance in the solar neighborhood, as well as constrain sulfur depletions onto grains. In addition, the Orion sample provides another data point to define the galactic disk sulfur abundance gradient.

2. OBSERVATIONAL DATA

The targets are 10 main-sequence early B-type star members of the Ori OB1 association, selected from the sample of Cunha & Lombard (1994) and previously analyzed for neon abundances in Cunha et al. (2006). The observational data are high-resolution (\( R \sim 35,000\)) spectra obtained with the Astrophysical Research Consortium (ARC) Echelle Spectrograph on the 3.5 m telescope at the Apache Point Observatory in 2007. The spectra cover the wavelength range between 3480 and 10260 Å and have signal-to-noise ratios generally greater than ~100. The data were reduced and the spectra were extracted and normalized to a unity continuum following standard procedures. In Figure 1, we show sample spectra for all target stars in the spectral region between 4800 Å and 4832 Å where the S ii lines at 4815 Å and 4824 Å are found. More details about the observations and data reduction can be found in Lanz et al. (2008).

3. STELLAR PARAMETERS AND SULFUR ABUNDANCE DETERMINATIONS

The stellar parameters, effective temperature, surface gravity, and microturbulent velocity, adopted in this analysis are listed
in Table 1 and taken from Cunha & Lambert (1994). The values of $T_{\mathrm{eff}}$ and $\log g$ in that study were obtained from an iterative scheme which combines photometric calibrations for the Strömgren indices $c_{\alpha}$, $[c_{1}]$, and $\beta$ and fitting of LTE theoretical profiles to the H$\gamma$ line wings. The microturbulence, $\xi$, was derived from an analysis of O$\,\text{ii}$ lines, by requiring that the oxygen abundances are independent of the line strength.

Sulfur abundances for a sample of 16 S$\,\text{ii}$ and 3 S$\,\text{iii}$ lines were derived from NLTE synthetic profiles and from adopting LTE model atmospheres from Kurucz (1993) plus a sulfur model atom from Vrancken et al. (1996). Our line sample was selected from the Kurucz line list and included all S$\,\text{ii}$ and S$\,\text{iii}$ lines within 4000–5100 Å with profiles that could be synthesized (corresponding to a minimum equivalent width $\sim$2 mÅ) and that were relatively free of blends. The adopted model atom treats S$\,\text{ii}$/S$\,\text{iii}$ simultaneously with 81 levels of S$\,\text{ii}$ and 21 levels of S$\,\text{iii}$ and also includes the three lowest levels of S$\,\text{i}$ and the two lowest levels of S$\,\text{iv}$, together with the ground state of S$\,\text{v}$. The solutions to the statistical equilibrium and transfer equations were obtained with the program DETAIL (Giddings 1981) which assumes LS-coupling.

Synthetic line profiles were calculated with the code SURFACE (Butler & Giddings 1985) and assuming Voigt profile functions. These profiles were then broadened by means of convolution with a rotational profile, including both the projected rotational velocity ($V \sin i$), limb darkening, and the instrumental profile. The microturbulence for each star was kept constant while abundances and $V \sin i$’s were allowed to vary.

![Figure 1. Sample observed spectra in the spectral region between 4800 and 4832 Å for all observed targets.](image)

### Table 1

| Star     | $T_{\mathrm{eff}}$ (K) | $\log g$ | $\xi$ (km s$^{-1}$) | $V \sin i$ (km s$^{-1}$) | $A$(S $\,\text{ii}$) | $A$(S $\,\text{iii}$) | $A$(S) |
|----------|------------------------|----------|---------------------|-------------------------|-----------------------|-----------------------|--------|
| HD 35039 | 20550                  | 3.74     | 8.0                 | 9 ± 1                   | 7.18 ± 0.16$^{[16]}$ | 7.14 ± 0.13$^{[3]}$ | 7.18 ± 0.15$^{[19]}$ |
| HD 35299 | 24040                  | 4.25     | 8.0                 | 12 ± 2                  | 7.12 ± 0.13$^{[16]}$ | 7.06 ± 0.07$^{[3]}$ | 7.11 ± 0.13$^{[19]}$ |
| HD 35912 | 19590                  | 4.20     | 8.0                 | 14 ± 2                  | 7.14 ± 0.14$^{[15]}$ | 7.15 ± 0.02$^{[2]}$ | 7.14 ± 0.13$^{[17]}$ |
| HD 36285 | 21930                  | 4.40     | 8.0                 | 14 ± 2                  | 7.15 ± 0.13$^{[15]}$ | 7.17 ± 0.10$^{[2]}$ | 7.15 ± 0.13$^{[17]}$ |
| HD 36351$^a$ | 22520              | 4.23     | 9.0                 | 31 ± 4                  | 7.09 ± 0.10$^{[7]}$ | 7.15 ± 0.01$^{[2]}$ | 7.11 ± 0.09$^{[9]}$ |
| HD 36591$^a$ | 26860              | 4.26     | 9.0                 | 11 ± 2                  | 7.06 ± 0.03$^{[2]}$ | 7.09 ± 0.11$^{[2]}$ | 7.07 ± 0.07$^{[4]}$ |
| HD 36959 | 24890                  | 4.41     | 6.0                 | 13 ± 3                  | 7.13 ± 0.14$^{[9]}$ | 7.24 ± 0.14$^{[3]}$ | 7.16 ± 0.14$^{[12]}$ |
| HD 37209 | 24080                  | 4.13     | 10.0                | 44 ± 8                  | 7.22 ± 0.05$^{[5]}$ | 7.20 ± 0.12$^{[2]}$ | 7.22 ± 0.06$^{[7]}$ |
| HD 37356 | 22370                  | 4.13     | 9.0                 | 20 ± 3                  | 7.15 ± 0.14$^{[13]}$ | 7.05 ± 0.14$^{[5]}$ | 7.13 ± 0.14$^{[16]}$ |
| HD 37744$^a$ | 24000              | 4.35     | 7.0                 | 38 ± 4                  | 7.27 ± 0.14$^{[3]}$ | 7.20 ± 0.04$^{[2]}$ | 7.24 ± 0.11$^{[5]}$ |

**Note.** $^a$ Revised $T_{\text{eff}}$ and $\log g$. 

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**Figure 1.** Sample observed spectra in the spectral region between 4800 and 4832 Å for all observed targets.
Figure 2. Sample fits showing synthetic profiles (red line) and observed spectra (black line) of a S\textsc{ii} line at 4815 Å and a S\textsc{iii} line at 4361 Å for the target stars HD 35299 and HD 37744. The best-fit $V\sin i$ and abundance values for each line are shown in the panels.  

(A color version of this figure is available in the online journal.)

The best fit for each line was obtained from the $\chi^2$-minimization of the differences between theoretical and observed profiles. The S\textsc{ii} and S\textsc{iii} transitions analyzed and atomic data (excitation potentials and oscillator strengths) are found in Table 2; the gf values are from the Opacity Project (Cunto & Mendonza 1992). In Figure 2, we show examples of best-fit synthetic profiles of S\textsc{ii} and S\textsc{iii} lines for the target stars HD 35299 and HD 37744.

Final sulfur abundance results (including S\textsc{ii} and S\textsc{iii} abundances) and $V\sin i$ values for the stars are presented in Table 1: these are the averages for the individual lines and the respective abundance dispersions are also listed (with the number of sulfur lines fitted for each star appearing in brackets). We note that the dispersions presented in the table represent the line-to-line scatter and are not representative of real uncertainties in the derived abundances. The total errors in our abundance analysis are estimated in Section 3.1. As a check, we compared the projected rotational velocities in Table 1 with $V\sin i$'s derived by adopting a calibration by Daflon et al. (2007) of full widths at half-maximum (FWHMs) of He\textsc{i} lines at $\lambda\lambda$4026, 4388, and 4471 Å measured from a grid of synthetic spectra calculated in NLTE. The comparison between the $V\sin i$'s obtained from sulfur lines with those using the He lines calibration is shown in Figure 3. We note a very good agreement between the two sets of $V\sin i$ values; except one star (HD 37209) for which the two determinations agree marginally, within the uncertainties ($V\sin i_{\text{Sulfur}} = 44 \pm 8$ km s$^{-1}$ and $V\sin i_{\text{Helium}} = 53 \pm 2$ km s$^{-1}$).

The analysis of sulfur in B stars is aided by the fact that lines from two ionization stages (S\textsc{ii} and S\textsc{iii}) can be observed and this offers the possibility to constrain the effective temperatures from the ionization balance between S\textsc{ii} and S\textsc{iii}. Spectroscopic $T_\text{eff}$'s, obtained from an agreement between the abundances from S\textsc{ii} and S\textsc{iii} lines, can provide an additional check on the adopted effective temperature scale for the studied stars (shown in Figure 4). For most stars in our sample, sulfur abundances derived from S\textsc{ii} and S\textsc{iii} lines (adopting the $T_\text{eff}$ scale from Cunha & Lambert 1994) were found to agree within $< 0.10$ dex. We note, however, that the stars HD 3651, HD 36591, and HD 37744 yielded differences in $A($S\textsc{iii} -- S\textsc{ii}$) of $+0.20$ dex,
Figure 4. Sulfur abundances of individual S II (open circles) and S III (open squares) lines as a function of the ionization potential \( \chi \), showing the sulfur ionization balance for the stars HD 35039 (top panel) and HD 36351 (bottom panel). The effective temperatures are from Table 1. The dotted lines represent the mean sulfur abundance for each star. (A color version of this figure is available in the online journal.)

+0.16 dex, and −0.17 dex, respectively. The strength of the S II lines reaches a maximum around \( T_{\text{eff}} = 18,000–19,000 \) K, whereas the S III lines are more sensitive to \( T_{\text{eff}} \) variations in this temperature range (see Figures 7–10 of Vrancken et al. 1996). It is likely that the differences between the abundances derived from S II and S III lines result from uncertainties in the adopted temperatures. We thus revised the effective temperatures of these three stars by +2.6%, +2%, and −2%, respectively, in order to bring S II and S III abundances into agreement. The log \( g \) values for these stars were also revised in order to obtain similar theoretical fits to the H\( \gamma \) profiles. These revised \( T_{\text{eff}} \) and log \( g \) values and the respective abundance results are listed in Table 1.

Sulfur abundance results for the Orion stars are plotted as a function of the adopted effective temperature in the upper panel of Figure 5. The effective temperatures of the stars in this sample encompass the range roughly between 20,000 K and 27,000 K and, although for B stars this represents a relatively broad range in \( T_{\text{eff}} \), no trends with abundance are observed. The flat distribution of sulfur abundances derived suggests that these results are probably free of major systematics within this \( T_{\text{eff}} \) range. In the lower panel of Figure 5, we present the difference between the abundances derived from S III and S II lines (\( A(\text{S III}) - A(\text{S II}) \)) also plotted as a function of the adopted \( T_{\text{eff}} \). The differences are small, \(< -0.10 \) dex, and do not show a significant trend with the effective temperature.

In order to briefly evaluate the importance of adopting a treatment in NLTE versus LTE when studying sulfur abundances in B-type stars, we computed LTE abundances for one target star HD 35299 with \( T_{\text{eff}} = 24,000 \) and log \( g = 4.25 \). The results from this test calculation indicate a modest correction for the average abundance of S II lines: \( \delta (A(\text{S II})_{\text{NLTE}} - A(\text{S II})_{\text{LTE}}) = -0.03 \) dex. This is a small effect in the average abundance but the S II line-to-line scatter in LTE is found to be much larger (\(< -0.25 \) dex) than in NLTE (\(< -0.15 \) dex). It should be noted that some of the S II lines, such as \( \lambda 4278.5 \), have significant NLTE corrections (\(< -0.7 \) dex); while others, such as \( \lambda 4269.7 \) and \( \lambda 4294.4 \) have relatively small NLTE corrections (\(< +0.04 \) dex). A reduced \( \chi \) scatter in the average NLTE abundance as opposed to LTE generally indicates that there is good consistency in the NLTE calculations of individual lines and adequacy of the adopted model atom. The NLTE corrections for the S III lines studied here are also not significant: \( \delta (A(\text{S III})_{\text{NLTE}} - A(\text{S III})_{\text{LTE}}) = -0.02 \) dex; the line-to-line S III scatter both in LTE and NLTE are found to be quite small.

3.1. Abundance Uncertainties

The abundance results in this study are based on a spectrum synthesis analysis and are subject to uncertainties arising mainly from the uncertainties in stellar parameters, microturbulent velocities, as well as placement of the continuum and \( g f \) values. In order to estimate the errors in the derived sulfur abundances,
we re-computed the abundances for HD 35299 (a sharp-lined star with $T_{\text{eff}} \sim 24,000$ K) by independently increasing each of the following parameters, one at a time, by 4% for $T_{\text{eff}}$, 0.1 dex for $\log g$, 1.5 km s$^{-1}$ for microturbulence, 0.5% for the continuum location, and 10% for $gf$ values. The sensitivity of the sulfur abundances to variations in these parameters is presented in Table 3. The combined errors in the derived $\text{S}^{\text{II}}$ and $\text{S}^{\text{III}}$ abundances are 0.11 dex and 0.10 dex, respectively.

The stellar parameters in this study were taken from Cunha & Lambert (1994) and these were obtained from an approach which combined Strömgren photometry and LTE theoretical profile fits to the H$_\beta$ line wings (Section 3). The adoption of LTE model profiles likely overestimates log $g$’s, in particular for hotter stars with $T_{\text{eff}} \sim 30,000$ K (Nieuw & Przybilla 2007). For the effective temperature range of the target stars, however, this effect is probably within the uncertainties in the determinations. In order to quantify the errors in log $g$, we did test calculations by re-deriving log $g$’s for two target stars (the coolest and the hottest in our sample) using NLTE theoretical profiles of H$_\beta$ calculated with DETAIL and SURFACE (K. Butler 2000, private communication). The results obtained indicate that the differences between (log $g_{\text{LTE}}$ - log $g_{\text{NLTE}}$) vary between 0.05 dex (for the coolest star in our sample) and 0.1 dex (for the hottest star in our sample). Such differences in log $g$ would result in sulfur abundance differences between $-0.01$ and $-0.02$ dex, at most (Table 3).

4. DISCUSSION

NLTE sulfur abundances are derived here for a sample of young B stars from the Orion association: the abundance distribution obtained in this study is homogeneous with a relatively small scatter which is roughly of the order of the abundance errors. The average sulfur abundance for our sample is $A(S) = 7.15 \pm 0.05$. In the following section, we will compare these results with the solar abundance.

4.1. Sulfur Abundances in Orion and the Solar Value

In recent years, the sulfur abundance which is recommended for the Sun has been revised downward by $\sim 0.15 – 0.20$ dex (see, for example, Lodders et al. 2009). The compilation of solar system abundances by Grevesse & Sauval (1998) listed a photospheric abundance of $A(S) = 7.33 \pm 0.11$. More recently, Asplund et al. (2006) did a critical evaluation of sample $\text{S}^{\text{II}}$ lines and removed those lines which were deemed to be blended. This study recommended a lower sulfur abundance of $A(S) = 7.14 \pm 0.05$ for the solar photosphere, in much better agreement with measurements in meteorites ($A(S) = 7.17 \pm 0.02$; Lodders et al. 2009). Note that the photospheric abundances discussed above were obtained using one-dimensional model atmospheres. An important confirmation of the one-dimensional result comes from the recent modeling of the forbidden $[\text{S}^{\text{I}}]$ line at 1082 nm by Caffau & Ludwig (2007), which is based on three-dimensional hydrodynamical model atmospheres, that finds a sulfur abundance extremely consistent with the one-dimensional results: $A(S) = 7.15 \pm 0.01$stat $\pm 0.05$sys.

The average sulfur abundance of the Orion B stars obtained here is found to be in perfect agreement with the solar system value: the abundances all cluster around $A(S) = 7.15$. Such an agreement, taken at face value, indicates that a non-measurable evolution of the sulfur abundances has taken place in the last $\sim 4.5$ Gyr. The consistency between the sulfur abundances measured for Orion and the Sun (both from one-dimensional and three-dimensional model atmospheres and meteorites) also argues favorably for the recent claim by Cunha et al. (2006) and Lanz et al. (2008) that the abundances of Ne and Ar measured in the Orion association can be considered as good proxies for the solar system abundances; this connection is especially interesting in the case of noble gases because the solar abundances of such elements are much more uncertain, yet these abundances need to be defined as they affect solar interior models.

4.2. Previous Results for Early-Type Stars

Recent studies of chemical abundances in OB stars have not analyzed sulfur (e.g., Przybilla et al. 2008; Simón-Díaz et al. 2006) and most of the sulfur abundances which are available in the literature are based on LTE treatments. For example, Gies & Lambert (1992) presented a detailed LTE analysis for a sample of early-type B stars focusing on CNO, but also derived $\text{S}^{\text{II}}$ abundances for the coolest B stars in their sample (with $T_{\text{eff}} < 24,750$ K). The mean sulfur abundance in that study is $A(S) = 7.21 \pm 0.12$, with a slight increase in the abundance as a function of effective temperature that could be explained in terms of the expected errors. On the other hand, Kilian (1994) analyzed a sample of seven stars in the Orion association and obtained $(A(S))_{\text{LTE}} = 6.80 \pm 0.25$. Their derived abundances show a trend with the effective temperature, and the authors suggest this may result from neglecting NLTE effects in their analysis.

Line formation in NLTE was considered in the study by Vrancken et al. (1996). The focus in that paper was on the construction and description of a fairly complete sulfur model atom (which is adopted in the present analysis), but the authors also derived abundances for three B stars as a test of their model atom, for which they obtained sulfur abundances in the range $A(S) = 7.14 – 7.38$. One of the stars studied in that paper, in particular, is also in our sample, HD 37356. For this star, they obtained $A(S) = 7.14 \pm 0.16$ (considering only $\text{S}^{\text{III}}$ lines), in full agreement with $A(S) = 7.13 \pm 0.14$, obtained here from 13 $\text{S}^{\text{II}}$ and 3 $\text{S}^{\text{III}}$ lines. More recently, Morel et al. (2006) used the same methodology as in Vrancken et al. (1996) and analyzed sulfur abundances (along with other elements) in a sample of nine $\beta$ Cephei stars. The average sulfur abundances found was $A(S) = 7.21 \pm 0.13$. The results from this sample were later combined with sulfur abundances of 11 stars (not all $\beta$ Cepheis; Morel et al. 2008) and the average sulfur abundance obtained is $A(S) = 7.18 \pm 0.11$. We note, however, that the results obtained for Cepheid stars (Andrievsky et al. 2002) are significantly higher than the above: the average sulfur abundance calculated for a sample of 24 Cepheids in the solar neighborhood (located within 7.6 and 8.2 kpc from the Galactic center) is $A(S) = 7.44 \pm 0.09$.

The first systematic NLTE abundance analysis of sulfur in a large sample of OB stars is presented in the series of papers by

| $\delta(T_{\text{eff}})$ | $\delta(\log g)$ | $\delta(T)$ | $\delta(gf)$ | $\delta$(continuum) | $\delta$(total) |
|------------------------|-----------------|-------------|-------------|---------------------|----------------|
| +4%                    | +0.1            | +1.5        | +10%        | +0.5%               | +11%           |
| +0.09                  | +0.02           | −0.04       | +0.04       | +0.03               | +0.11          |
| −0.08                  | +0.01           | −0.04       | +0.04       | +0.03               | +0.10          |

Table 3: Abundance Uncertainties
Daflon et al. (2003, 2004a, 2004b). The sulfur abundances in these previous studies from our team, however, were based only on two weak S III lines at 4361 and 4364 Å, which fall close to the edge of the red wing of Hγ. It should be noted that for the majority of their targets, the S III line at 4364 Å was the only measured line, even for target stars with the lowest V sin i’s and having spectra with the highest signal-to-noise ratios. The target sample analyzed in these studies covered mostly the solar neighborhood and the inner Galactic disk (galactocentric distances Rg between ∼5 and 9 kpc) but also included four more distant targets (Rg ∼ 9–14 kpc) which helped in the definition of disk metallicity gradients as discussed in Daflon & Cunha (2004).

### 4.2.1. Sulfur Abundance Gradients

The sulfur abundance results from Daflon & Cunha (2004) are shown versus the adopted galactocentric distances in Figure 6 (open circles). The sulfur results for Orion are shown as open triangles and these seem to agree well with the overall trend. The overlap between the abundance results in the solar neighborhood is clear. In particular, if one averages the abundances of all stellar members of the five OB associations located within Rg = 7.6–8.2 kpc, which are Cep OB2, Cep OB3, Cyg OB3, Cyg OB7, and Lac OB1, the average sulfur abundance for this nearby subsample is A(S) = 7.19 ± 0.09: this compares well with the average sulfur abundance obtained for Orion, which is located ∼500 pc from the Sun, and gives support to previous results (Przybilla et al. 2008) that the solar neighborhood abundance is homogeneous, at least at the level of the uncertainties in the abundance analysis.

Such agreement in the abundance results for the solar neighborhood is pleasing since the sulfur abundances derived here are based on several lines from two ionization stages (S II and S III), while the previous analyses were obtained from one, or a maximum of two, sulfur lines from a single ionization stage (S III), and from a different T eff scale: the T eff’s from Daflon & Cunha (2004) are based on a calibration for the reddening-free parameter Q, and the effective temperatures from Cunha & Lambert (1994) are based on an iterative scheme that combines photometric calibrations for Strömgren indices and the fitting of Hα wings.

Since there seems to be no major systematic differences between the sulfur abundances previously published by our group and from this study, the Orion results can be added to compute a new sulfur gradient for the Galactic disk. A linear fit to the run of abundances with distances from the Galactic center is a possible simple description for the overall decrease in the sulfur abundances toward the edge of the disk. The best-fit straight line to the complete data set in Figure 6 corresponds to A(S) = (7.481 ± 0.097) − (0.037 ± 0.012)Rg. The adopted distances are from Daflon & Cunha (2004). The sulfur gradient obtained is flat, in line with the previous result obtained by Daflon & Cunha (2004), and very similar to the previously derived oxygen gradient for the same target sample. A similar behavior between sulfur and oxygen is expected as these are both α-elements.

### 4.3. Sulfur Depletion

The Orion Nebula is largely considered a standard reference for the ionized gas abundances in the local neighborhood (see, for instance, Esteban et al. 2004). However, the direct comparison between the abundance derived for a particular element in the Nebula and in the Sun should consider two important points: first, its depletion onto grains, and second, the effects of the chemical evolution of the solar neighborhood since the Sun was formed. Concerning the evolutionary effects, chemical evolution models by Chiappini et al. (2003) indicate only a small effect, of the order of ∼0.1 dex, on the sulfur evolution between the formation of the solar system and the present.

Concerning the more general discussion about the depletion of sulfur onto grains, there are clear indications that sulfur is undepleted in diffuse interstellar gas. Howk et al. (2006) derive a gas-phase sulfur abundance of A(S) = 7.13 ± 0.03 for the Galactic Halo interstellar medium. In denser regions, however, the amount of sulfur depletion is not completely clear. Tieftrunk et al. (1994) considered gas-phase abundances in S-bearing molecules and argued that sulfur depletions of factors of ∼10^3 could exist. Also, dominant S^+ ions (of this easily ionized element) can efficiently freezeout onto negatively charged dust grains in denser regions (Ruffle et al. 1999). Puzzling contrary indications exist, as evidenced by the presence of S III recombination lines in dense clouds and the absence of strong infrared sulfur features in grains—see Goicoechea et al. (2006) for a discussion. One way to gain insight into this problem is to study photodissociated regions (PDR), which are intermediate between diffuse and dark clouds as, for example, the Horsehead PDR (Goicoechea et al. 2006). Even in an environment with large chemical complexity, low sulfur depletion has been found.

In order to constrain the amount of sulfur depletion in the Orion H II region, one can directly compare the sulfur abundances of young early-type star members of the OB association with the chemical composition of the Orion Nebulae, albeit keeping in mind that there may be systematic abundance errors which afflict both the stellar and nebular analysis independently. The chemical composition of the gas which formed the young stars in the Orion association (and which can be measured in the stellar photospheres of OB stars) represents an independent check on the present-day gas content, which is measured from nebular lines in its H II region.

The most recent and detailed study of the chemical composition of the Orion Nebulae by Esteban et al. (2004) observed a region near the hot star θ^1 Ori, and measured A(S) = 7.22 ± 0.04;
when adopting their preferred value for the temperature fluctuation parameter, $r^2 = 0.02$ (see Figure 5 showing the results obtained for the young stars in Orion comparison with the dotted line which represents the sulfur abundance for the Orion Nebulae from Esteban et al. 2004). Although it should be kept in mind that the stellar and nebular abundances in Orion agree within the quoted errors in the determinations, a brief comparison of the results is of interest. The difference between the nebular and stellar abundances is found to be positive ($\Delta A(S)_{neb-Stel} = +0.07$ dex) and not explainable as the result of the chemical evolution sulfur as the Orion stars are very young, with ages less than $\sim 10$ million years. Since the net effect of entrapment of gas onto grains is to reduce the gas-phase abundance, the nebular abundance could be viewed as a lower-limit abundance value. If the lowest sulfur abundance value in Esteban et al. (2004) of $A(S) = 7.06$ is adopted (which corresponds to the extreme case of $r^2 = 0.0$; not favored by the authors), the amount of sulfur depletion using the B stars as a reference would still be modest or nonexistent within the uncertainties. It is easily arguable from these results and their respective uncertainties that sulfur cannot be significantly depleted in the Orion Nebulae.

5. CONCLUSIONS
Sulfur abundances are derived in NLTE for a sample of young B stars of the Orion association. The conclusions from this study are the following.

1. The abundance distribution in Orion is found to be homogeneous within the uncertainties in the analysis. The comparison of sulfur abundances derived for Orion B stars with abundance results for the Sun, the interstellar medium, and early-type stars in the solar vicinity allows us to conclude that the sulfur abundances have undergone very little change from the time of formation of the solar system $\sim 4.5$ Gyr ago.

2. The close agreement between the sulfur abundances in Orion and the Sun provides indirect support to previous claims by Lanz et al. (2008) and Cunha et al. (2006) that the young Orion stars can be used as good proxies in order to ascertain the solar abundances of noble gases, such as Ne and Ar, whose abundances are not measurable in the solar photosphere.

3. The abundances of main-sequence B stars overlap with the gas-phase abundance derived by Esteban et al. (2004) for the Orion Nebula. The similarity between these abundances indicates that sulfur is undepleted in the Orion Nebula. Contrary to elements such as C and Fe, for which important depletion exists, sulfur appears to be a remarkably direct metallicity indicator of the Galactic disk (except perhaps in very dense regions).

4. The sulfur abundance results for Orion are added to a database of abundances previously published for OB main-sequence stars along the Galactic disk. The new sulfur abundance gradient computed for a sample of 50 OB stars is $A(S) = (7.481 \pm 0.097) - (0.037 \pm 0.012)R_g$. The sulfur gradient is very similar to the flat gradient of $-0.031 \pm 0.012$ dex kpc$^{-1}$ previously obtained for oxygen in Daflon & Cunha (2004) and in agreement with standard chemical evolution model predictions such as Chiappini et al. (2001) and Cescutti et al. (2007).

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