

# The chemical composition of the Orion star forming region: stars, gas and dust

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**Abstract:** We present a summary of main results from the studies performed in the series of papers *The chemical composition of the Orion star forming region*. We reinvestigate the chemical composition of B-type stars in the Orion OB1 association by means of state-of-the-art stellar atmosphere codes, atomic models and techniques, and compare the resulting abundances with those obtained from the emission line spectra of the Orion nebula (M42), and recent determinations of the Solar chemical composition.

## 1 Introduction

For many years, our knowledge about the chemical composition of early-B main sequence stars in the Solar vicinity has been characterized by two main results: (i) the derived abundances were highly inhomogeneous (with a dispersion of up to 0.5 dex), and (ii) the mean values indicated lower abundances than the standard set of Solar abundances (Grevesse & Sauval 1998, GS98) Some recent results have begun to change this situation. The Solar oxygen abundance traditionally considered as a cosmic abundance reference (GS98) was revised by Asplund et al. (2004) to a value of  $\epsilon(\text{O}) = 8.66$  dex, 0.17 dex lower than the standard value. This was the beginning of what has been called the epoch of the “solar crisis”: between 2004 and 2008, several studies by different authors (see references in Simón-Díaz 2010) presented solar oxygen abundances derived by means of different approaches. The calculated values range from 8.63 dex (Socas-Navarro & Norton 2007) to 8.86 dex (Centeno & Socas-Navarro 2008). The debate about its actual value is still open<sup>1</sup>. Przybilla, Nieva & Butler (2008, PNB08) analyzed a representative sample of six unevolved early B-type stars in nearby OB associations and the field, and found a very narrow distribution of abundances, with mean values that are larger compared to previous works. PNB08 indicate the importance of properly determining the atmospheric parameters and using robust model atoms to avoid systematic errors in the abundance determination. The study by PNB08 shows that the chemical inhomogeneity previously found for B-type stars in the Solar vicinity may be spurious as a consequence of those systematic errors.

<sup>1</sup>The present solar O abundance indicated in Asplund et al. (2009) is 8.69 dex.

## **1.1 Orion OB1 and M 42**

The Orion complex, containing the Orion molecular cloud and the Orion OB1 (Ori OB1) association, is one of the most massive active star-forming regions in the 1 kpc centered on the Sun. Blaauw (1964) divided Ori OB1 into four subgroups of stars, namely Ia, Ib, Ic, and Id, having different locations in the sky and different ages. Brown et al. (1994) derived mean ages of 11.4, 1.7, 4.6, and <1 Myr for subgroups Ia to Id, respectively. The youngest subgroup Ori OB1 Id is associated with the Orion nebula (M 42), the brightest and most studied H II region and the closest ionized nebula to the Sun in which a high accuracy abundance analysis can be performed. The correlation between the ages of the stellar subgroups, their location, and the large scale structures in the interstellar medium around Ori OB1 have been interpreted as features of sequential star formation and Type-II supernovae (Reynolds & Ogden 1979, Cowie et al. 1979, Brown et al. 1994).

## **1.2 B-type star abundances in Orion**

Cunha & Lambert (1992, 1994, CL92,94) obtained C, N, O, Si, and Fe abundances of 18 B-type main sequence stars from the four subgroups comprising the Ori OB1 association. They found a range in oxygen abundances of 0.4 dex, with the highest values corresponding to the stars in the youngest (Id and some Ic) subgroups. In this case, the inhomogeneity in stellar abundances (mainly oxygen and silicon) seemed to be real and coherent with a scenario of induced star formation in which the new generation of stars were formed from interstellar material contaminated by Type-II supernovae ejecta. The study by CL92,94 was based on a photometric estimation of  $T_{\text{eff}}$  and the fitting of the  $H\gamma$  line computed from Kurucz (1979) LTE model atmospheres to derive  $\log g$ . In view of the results by PNB08 a reinvestigation of the chemical composition of B-type stars in Ori OB1 was warranted.

In the series of papers *The chemical composition of the Orion star forming region* we aimed at (i) investigating whether the inhomogeneity of B-type star abundances previously found is real, and (ii) comparing the derived abundances with recent determinations of the Solar chemical composition, abundances in other B-type stars in the Solar vicinity, and the nebular abundances derived from the emission line spectrum of the Orion nebula. We summarize here the main results from three papers in the series.

## **2 Homogeneity of O and Si abundances in B-type stars**

In Simón-Díaz (2010, Paper I) we investigated whether the inhomogeneity of abundances previously found in B-type stars in the Ori OB1 association is real or a consequence of intrinsic errors induced by the use of photometric indices to establish the stellar parameters prior to the abundance analysis. We obtained a high quality spectroscopic data set comprising 13 B-type stars in the various Ori OB1 associations (see Simón-Díaz et al. 2011), and performed a detailed, self-consistent spectroscopic NLTE abundance analysis by means of the modern stellar atmosphere code FASTWIND (Puls et al. 2005).

Main results of this study are summarized in Figure 1 and Table 1. We detected systematic errors in the stellar parameters determined previously which affected the derived abundances. Once these errors were accounted for, we find a high degree of homogeneity in the O and Si abundances for stars in the four Ori OB1 subgroups. The dispersion of abundances for the 13 stars is smaller than the intrinsic uncertainties (0.10 and 0.08 dex for O and Si, respectively).

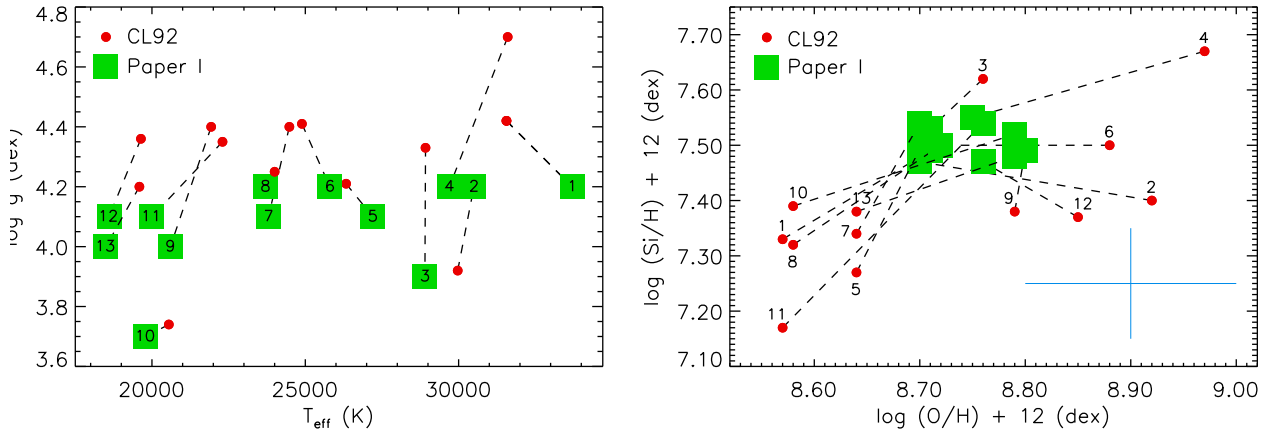


Figure 1: Comparison of stellar parameters, and O and Si abundances derived in Paper I and CL92. The cyan cross represents the mean intrinsic uncertainties for O and Si abundances. Numbering follows the order in Table 2 from the original paper.

Table 1: Mean O and Si abundances derived from stars in each of the subgroups in Ori OB1. The global mean abundances are also indicated (FASTWIND analysis, Paper I).

Group	$\epsilon(\text{O})$	$\epsilon(\text{Si})$
Ia	$8.77 \pm 0.04$	$7.50 \pm 0.02$
Ib	$8.70 \pm 0.01$	$7.53 \pm 0.01$
Ic	$8.74 \pm 0.04$	$7.50 \pm 0.03$
Id	$8.72 \pm 0.04$	$7.51 \pm 0.06$
Global	$8.74 \pm 0.04$	$7.51 \pm 0.03$

Table 2: Mean C, N, Ne, Mg and Fe abundances from B stars in Ori OB1 (ADS analysis, Paper III). Intrinsic uncertainties from individual star analyses are indicated in parentheses.

Element	Mean abundance
C	$8.35 \pm 0.03$ (0.09)
N	$7.82 \pm 0.07$ (0.09)
Ne	$8.09 \pm 0.05$ (0.09)
Mg	$7.57 \pm 0.06$ (0.03)
Fe	$7.50 \pm 0.04$ (0.10)

The mean oxygen and silicon abundances agree with those resulting from a similar analysis of a representative sample of unevolved early B-type stars in the Solar neighbourhood (PNB08). Both results indicate that abundances derived from these stellar objects are more homogeneous and metal rich than previously thought.

We also compared the O and Si stellar abundance in Ori OB1 with those obtained for the Sun during the epoch of the "solar crisis". The O abundances in our sample of stars in Ori OB1 lay in the middle of all these values. In view of the present-day results the only thing we can say is that oxygen abundances in the Sun and B-type stars in the solar vicinity are the same within the uncertainties. However, we consider too premature to launch any firm conclusion or hypothesis about the chemical evolution of the local interstellar medium during the lifetime of the Sun. Silicon abundances are also very similar (contrarily to what was previously found from the study of B-type stars).

### 3 C, N, Ne, Mg, and Fe abundances in B-type stars revisited

In view of the results found in Paper I, a reinvestigation of other stellar abundances was warranted. In Nieva & Simón-Díaz (in prep., paper III) we derive C, N, Ne, Mg and Fe NLTE abundances for the stars analyzed in Paper I, following the procedure described in Nieva & Przybilla (2007, 2008). The strategy (ADS analysis) is based on a similar self-consistent spectroscopic analysis, but using

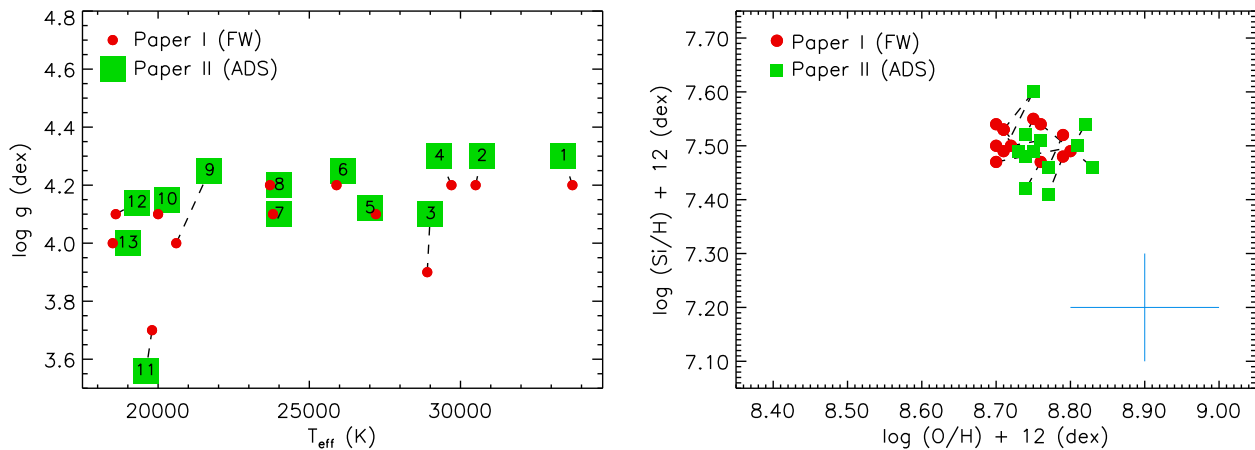


Figure 2: Comparison of stellar parameters, and O and Si abundances derived in Papers I and III (FW and ADS analyses, respectively). The cyan cross represents the mean intrinsic uncertainties for O and Si abundances. Same numbering as in Fig. 1.

ATLAS9 (Kurucz 1993) + DETAIL+SURFACE (Giddings 1981, Butler & Giddings 1985, plus recent updates).

We first compare the stellar parameters, O and Si abundances resulting from the FASTWIND (FW) and ADS analyses to be sure that both techniques provide similar results (see Figure 2). We find very good agreement within the uncertainties. Then we obtain abundances for C, N, Ne, Mg, and Fe by means of the ADS analysis (see final mean values from the analysis of 13 stars in the various subgroups from Ori OB1 in Table 2). Again, the dispersion of abundances for the 13 stars is smaller than the intrinsic uncertainties, indicating a high degree of homogeneity in the present-day abundances of these elements in the Orion star forming region (as derived from B-type stars).

## 4 Stars, gas and dust: the abundance discrepancy conundrum

In Simón-Díaz & Stasińska (2011, paper II), we re-examined the nebular abundance discrepancy problem which arises from the use of recombination lines (RL) on the one hand and collisionally-excited lines (CEL) on the other (see García-Rojas & Esteban 2007, and references therein) in the light of the high quality abundance determinations for B-type stars performed in Papers I and III. We reevaluated the CEL and RL abundances of several elements in the Orion nebula using the spectroscopic data set presented by Esteban et al. (2004) and ionization correction factors (ICFs) for unseen ions obtained by means of a photonization model suited for our purposes. The derived nebular abundances are compared with the mean stellar abundances obtained in Papers I and III (see Fig. 3). In particular, for the case of oxygen, we estimated the amount of oxygen trapped in dust grains for several scenarios for dust formation and compare the resulting gas+dust nebular abundances with the stellar abundances. Our study leads us to the conclusion that the oxygen abundances derived in the Orion nebula from CELs are incompatible with the abundances derived in the B stars (once the effects of depletion in dust grains are taken into account) while RL oxygen abundances are in better agreement (see Fig. 4).

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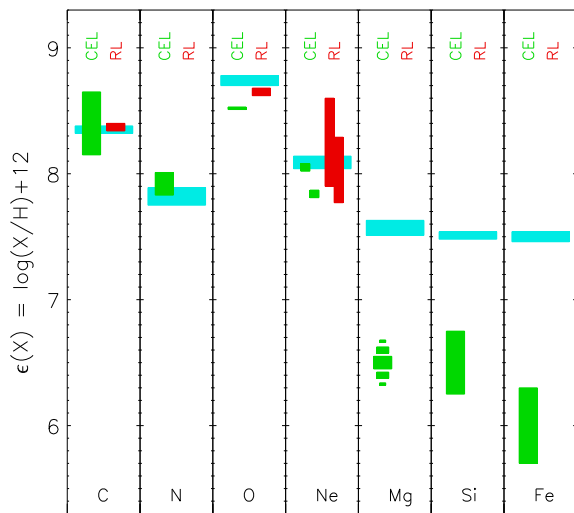


Figure 3: Comparison of C, N, O, Ne, Mg, Si and Fe abundances obtained from B-type stars (cyan), CEL (green), and RL (red). For Ne, there are two green boxes, corresponding to different ICFs (see paper II). The height of the boxes represents the uncertainties. Note that for Mg there is no evaluation of the uncertainty. A more detailed comparison (also including dust depletion) for oxygen is presented in Fig. 4.

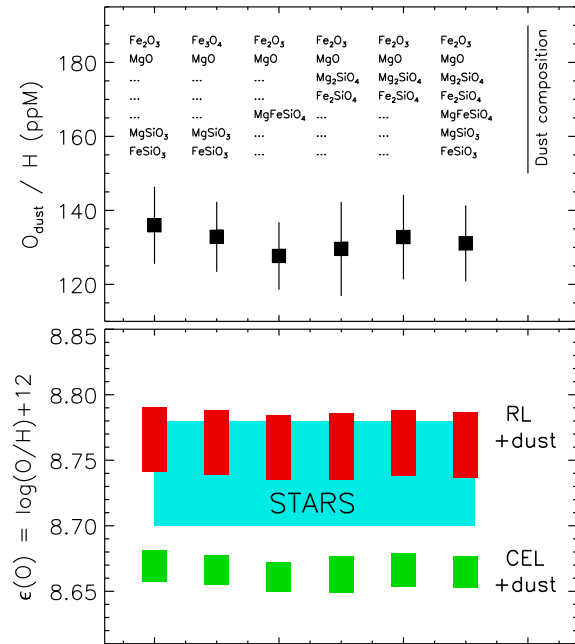


Figure 4: Upper panel: Amount of oxygen expected to be in solid form for various dust composition scenarios (see paper II). Lower panel: Comparison of the stellar oxygen abundance (wide cyan rectangle) with the gas+dust oxygen abundance in the nebula for the different dust scenarios. Green rectangles are obtained with CEL gas abundances, red rectangles are obtained with RL gas abundances.

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