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NEON ABUNDANCES IN B STARS OF THE ORION ASSOCIATION: SOLVING THE SOLAR MODEL PROBLEM?

Katia Cunha[1]
National Optical Astronomy Observatory, P.O. Box 26732, Tucson, AZ 85726; kcunha@noao.edu
Ivan Hubeny
Steward Observatory, University of Arizona, Tucson, AZ 85712; hubeny@aegis.as.arizona.edu
and
Thierry Lanz
Department of Astronomy, University of Maryland, College Park, MD 20742; tlanz@umd.edu
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ABSTRACT

We report on non-LTE Ne abundances for a sample of B-type stellar members of the Orion association. The abundances were derived by means of non-LTE fully metal-blanketed model atmospheres and extensive model atoms with updated atomic data. We find that these young stars have a very homogeneous abundance of $A(\mathrm{Ne}) = 8.11 \pm 0.04$. This abundance is higher by ∼0.3 dex than the currently adopted solar value, $A(\mathrm{Ne}) = 7.84$, which is derived from lines produced in the corona and active regions. The general agreement between the abundances of C, N, and O derived for B stars with the solar abundances of these elements derived from three-dimensional hydrodynamical models atmospheres strongly suggests that the abundance patterns of the light elements in the Sun and B stars are broadly similar. If this hypothesis is true, then the Ne abundance derived here will help to reconcile solar models with helioseismological observations.

Subject headings: stars: abundances — stars: early-type

Online material: color figures

1. INTRODUCTION

One important recent result from studies of stellar atmospheres and chemical compositions in stars is the downward revision in the abundances of carbon, nitrogen and oxygen in the solar photosphere, which was obtained from the adoption of time-dependant, hydrodynamical and three-dimensional model atmosphere calculations (Asplund 2005). These more realistic model atmosphere calculations indicate that the solar abundances should be lower by roughly 0.2–0.3 dex when compared to abundances derived from hydrostatic one-dimensional calculations. It soon became apparent that the significantly lower abundances in the Sun resulted in severe inconsistencies between the solar models and measurements from helioseismology.

Different possibilities were investigated in order to try to reconcile the solar models with the seismological observations, such as updating opacities (Bahcall et al. 2005b), changing diffusion rates (Guzik et al. 2005), or significantly changing the adopted solar abundances of key elements, such as neon. Allowing for a larger neon abundance, in particular, was justified because the neon abundance in the Sun can be considered to be more uncertain given that it is not measured from lines formed in the solar photosphere. Antia & Basu (2005) constructed envelope models of the Sun, allowed for different abundance mixtures and focused on the density profile, which is determined from helioseismology. More complete calculations were presented in Bahcall et al. (2005a) who constructed solar models, consisting of the atmospheres plus the interior, and concluded that an adopted neon abundance $A(\mathrm{Ne}) = 8.29 \pm 0.05$, would suffice in order to bring the solar models and seismological observations into an acceptable agreement. Independently, measurements of neon abundances in a sample of chromospherically active cool stars by Drake & Testa (2005) indirectly supported high Ne abundances in solar type stars.

It has been a long-standing puzzle that the C, N and O abundances obtained for B stars, which are young, were typically lower than the generally accepted solar abundances at the time from Anders & Grevesse (1989). These were puzzling results because from our simplest understanding of how the Galaxy chemically evolves, it is not expected that young stars in the solar vicinity would be less enriched than the Sun, which is much older. Moreover, the abundances obtained from Galactic H II regions were also lower than the accepted solar and in rough agreement with the B star results. These inconsistencies between the abundances of young stars and H II regions, on one hand, and the Sun on the other are reconciled nowadays with the revised solar abundances from three-dimensional models. In this context, it is therefore important and timely to derive accurate neon abundances in the atmospheres of early-type stars. In this study, we report on non-LTE (NLTE) neon abundance calculations for a sample of B stars members of the Orion association. The Ne abundances in young stars can independently shed light on the issue related to the reference Ne abundance in the Galaxy.

2. OBSERVATIONS

The target stars are OB main-sequence members of the different stellar subgroups of the Orion association and drawn from the sample analyzed by Cunha & Lambert (1992, 1994). Eleven stars were observed with the 2.1 m telescope at the McDonald Observatory at high resolution ($R = 55{,}000$) using the Sandiford echelle. The spectra were obtained on 1994 October 27 and these have 26 echelle orders covering the total spectral range between 5390 and 6680 Å. The spectra were reduced with IRAF data package following standard procedures.[2]

[1] On leave from Observatório Nacional-MCT, Rio de Janeiro, Brazil.

[2] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

TABLE 1
SAMPLE STARS AND ABUNDANCES

Star	$T_{\rm eff}$	log *g*	*A*(Ne)	*A*(O)
HD 35039	20,550	3.74	8.10	8.60
HD 35299	24,000	4.25	8.18	8.57
HD 35912	19,590	4.20	8.07	8.70
HD 36285	21,930	4.40	8.12	8.80
HD 36351	21,950	4.16	8.08	8.76
HD 37356	22,370	4.13	8.15	8.67
HD 37209	24,050	4.13	8.10	8.83
HD 37744	24,480	4.40	8.17	8.63
HD 36959	24,890	4.41	8.07	8.76
HD 36591[a]	26,330	4.21	8.09	8.60
HD 36960	28,920	4.33	8.08	8.72

[a] Recent results from *IUE* flux, 2MASS, and Johnson magnitudes (Nieva & Przybilla 2006) indicate quite good agreement with the adopted stellar parameters.

3. NON-LTE ABUNDANCE CALCULATIONS

The stellar parameters for the sample stars were derived in Cunha & Lambert (1992). NLTE model atmospheres were computed using the TLUSTY code (Hubeny 1988; Hubeny & Lanz 1995). The model calculations assumed a constant microturbulence of 2 km s^{-1}. Preliminary models for this study were taken from an extensive grid of NLTE line-blanketed model atmospheres of B stars (T. Lanz & I. Hubeny 2006, in preparation). The final models were computed for the actual effective temperatures and surface gravities of our program stars and adopting an extended Ne model atom. The BSTAR model grid is analogous to the OSTAR2002 grid (Lanz & Hubeny 2003), the only difference being the addition of lower ionization stages of the most important species. Concretely, the following ions were considered explicitly in the BSTAR grid models: H I–II, He I–III, C I–V, N I–VI, O I–VI, Ne I–V, Mg II–III, Al II–IV, Si II–V, S II–VI, and Fe II–VI.

The Ne model atom constructed consists of 79 levels of Ne I, 138 levels of Ne II, 38 levels of Ne III, 12 levels of Ne IV, plus ground state of Ne V. The energies of the levels were taken from the Opacity Project database TOPBASE (Cunto et al. 1993), updated by the more accurate experimental level energies from the Atomic and Spectroscopic Database at NIST (Martin et al. 1999) whenever available. The *gf*-values were taken from the same sources. However, since the *LS* coupling, on which the Opacity Project calculations are based, is rather inaccurate for Ne I, we have used results and the procedure suggested by Seaton (1998) to transform the level energies (and designations) from *LS* coupling to the more appropriate *jK* coupling. We also used a model atom that treats explicitly the fine structure of multiplets. The photoionization cross sections were taken from TOPBASE, the collisional excitation rates were considered using the Van Regemorter (1962) formula, including a modification for neutral atoms (as also used by Auer & Mihalas [1973]); for collisional ionization the Seaton formula was used (for a synopsis of expressions, see Hubeny [1988]).

The detailed synthetic spectra were computed using the interactive data language (IDL) interface SYNPLOT (I. Hubeny 2006, private communication) to the spectrum synthesis program SYNSPEC (Hubeny et al. 1995). The abundances were obtained from the best fits between observed and synthetic spectra of 8 Ne I transitions: 6506.5, 6402.2, 6383.0, 6334.5, 6266.5, 6163.5, 6143.1, and 6096.2 Å. We have computed NLTE line profiles (using NLTE atomic level populations of all atoms and ions computed by TLUSTY). When computing detailed synthetic spectra we found that the best fits to the observations were obtained for a microturbulent velocity around 5 km s^{-1}, although the abundance results were quite insensitive to the microturbulence parameter.

The nature of NLTE effects in Ne I line formation was already discussed by Auer & Mihalas (1973), Dworetsky & Budaj (2000), and Sigut (1999). Our models do not offer anything fundamentally different from these studies, only we are using significantly more extended model atoms, more recent atomic data, and fully blanketed model atmospheres. The nature of NLTE effects for the above listed optical lines of Ne I was already explained in the earlier studies, namely, since the lower levels of the optical lines are connected to the ground state of Ne I by resonance lines that are located in far UV, they are essentially in detailed balance with the ground state. The optical lines thus behave like classical lines in a two-level atom that is the lower level is somewhat overpopulated, while the upper level is depopulated (because of an imbalance of the number of excitations compared to deexcitations caused by the photon escape through the boundary). The source function is thus lower than the Planck function, and the optical lines are consequently predicted stronger than in LTE. This in turn means that the deduced NLTE abundances are expected to be lower that the LTE ones.

Our calculations are in good agreement with the results from earlier studies in the literature. Dworetsky & Budaj (2000) have also used the TLUSTY code and made their TLUSTY-compatible Ne I atomic data input available online. We did test calculations with their input data and found good agreement. A comparison with the calculations by T. A. A. Sigut (2006, private communication) was done from equivalent width measuments for target star HD 35299, and a good agreement was obtained.

3.1. Ne *Abundance Results and Previously Derived* O *Abundances*

The studied Orion stars span a significant range in effective temperature, from ~20,000 to 29,000 K (Table 1). In Figure 1 (*top*) we show that there is no significant trend of the Ne abundances with the stars' effective temperature, indicating the absence of important systematic errors in this study. A comparison between the LTE and NLTE abundance trend with $T_{\rm eff}$ is shown in the bottom panel of Figure 1. There is a trend of the derived LTE abundances with $T_{\rm eff}$, which again demonstrates the inadequacy of LTE for Ne abundance determinations, as already shown by earlier investigations. The LTE line profiles were obtained by setting the Ne level populations to their LTE values, while the atmospheric structure (temperature, electron density, etc.), as well as level population of other species, were kept at their NLTE values. We stress that such line profiles are different from truly LTE line profiles (computed for a consistent LTE structure and LTE level populations of all species), but our "LTE" line profiles best demonstrate NLTE effects in determining the Ne abundance. The fact that LTE abundances are *larger* than NLTE ones is in fact quite comforting in the context of Ne abundance determinations, because otherwise, one may be worried whether the deduced high Ne abundance is an artifact of some spurious NLTE effect caused for instance by some inadequacy in atomic data. However, since the NLTE abundance is *smaller*, this potential worry can be ruled out.

The Ne abundances obtained for the targets (listed in Table 1) are quite homogeneous and show a small scatter that can be completely explained in terms of uncertainties in the abundance de-

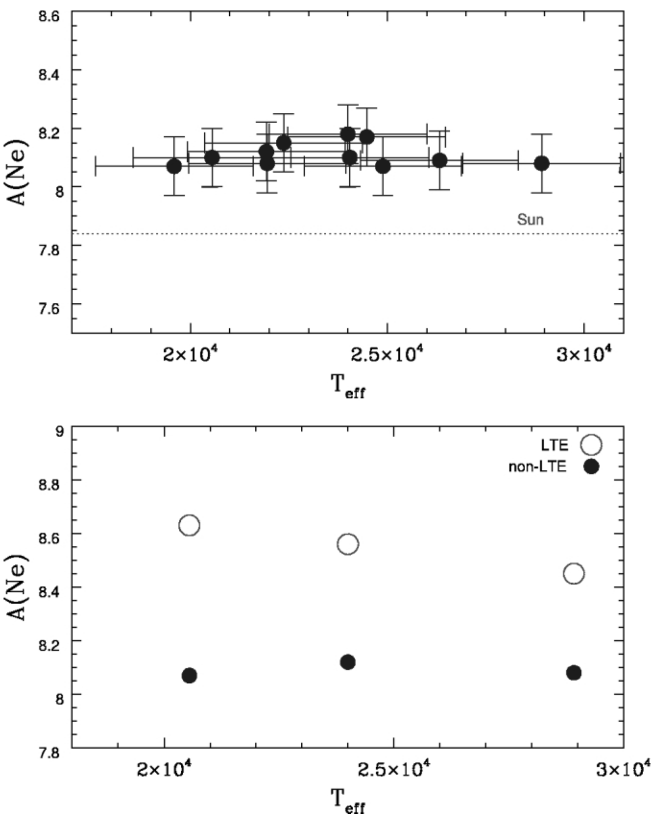

FIG. 1.—*Top*: Ne-derived abundances vs. the adopted effective temperatures for the sample Orion stars. The $T_{\rm eff}$ range covered here is relatively large and no trends are found for the derived neon abundances. For comparison, we also indicate the currently adopted solar Ne abundance from Asplund et al. (2005) as the dashed line. *Bottom*: LTE (*open circles*) and NLTE (*filled circles*) abundances calculated for the strongest Ne I line λ 6402. This is the only line that is strong enough to be measured in the hottest stars in our sample. The LTE Ne abundances are found to have a trend with effective temperature. This trend is erased with the NLTE calculations. [*See the electronic edition of the Journal for a color version of this figure*.]

terminations. The average Ne abundance for all target stars is $A(\mathrm{Ne}) = 8.11 \pm 0.04$. The uncertainties in the Ne I abundances can be estimated from the sum in quadrature of the abundance uncertainties due to errors in the adopted stellar parameters, microturbulence, continuum location, as well as atomic data. We estimate that our derived Ne abundances are accurate to within roughly 0.1 dex. The data available to us do not allow for Ne II abundances to be derived in this study as a consistency check. (We note that Kilian-Montenbruck et al. [1994] found high LTE Ne II abundances for OB stars.)

It is the Ne/O ratio and not only neon that is obtained from abundance measurements in the solar corona and this ratio constitutes an important ingredient in the construction of solar models. Before a comparison can be done with the Orion results for B stars, it is important to stress that the oxygen and neon abundances for the Orion targets were not derived homogeneously. The methodology presented in this study to derive neon abundances consisted of a full NLTE treatment, including NLTE line formation and the computation of fully-blanketed model atmospheres in NLTE. For oxygen, however, we adopt the previously published results from Cunha & Lambert (1994), which were derived in LTE, using Kurucz LTE model atmospheres, and finally corrected by means of the NLTE calculations by Becker & Butler (1988). It is important then to verify whether the previously derived oxygen abundances for Orion are consistent with results from the more sophisticated calculations presented here for neon.

As a consistency check on the published oxygen results, we rederived the oxygen abundance for one of the Orion stars, HD 35299, using TLUSTY SYNSPEC. We adopted the same published equivalent widths for O II lines and same stellar parameters but used the TLUSTY NLTE model atmospheres calculated for the Ne analysis. We calculated O II abundances versus the microturbulence parameter and derived $\xi = 5$ km s^{-1} and an oxygen abundance $A(\mathrm{O}) = 8.65 \pm 0.05$. This abundance compares favorably with the oxygen abundance obtained in Cunha & Lambert (1992), within the uncertainties. Such agreement justifies the adoption of the published oxygen results in order to investigate Ne/O ratios.

4. DISCUSSION

Solar photospheric abundances can be readily compared to meteoritic C1 chondrite abundances and good agreement is found for most of the elements, or more specifically, for those elements that form rocks (see, e.g., Lodders 2003). Noble gases, as well as carbon, nitrogen and oxygen, are volatiles, and their abundances are therefore significantly depleted in meteorites. For C, N, and O one can rely on abundances measured in the solar photospheres, available from both one-dimensional and three-dimensional model atmospheres calculations. For neon, however, the solar abundances are subject to further uncertainties due to the absence of photospheric lines, because even the lower excited states of the Ne atom have very high energy. Alternatively, Ne abundances in the Sun are inferred from measurements of Ne/O in the solar coronal gas, solar wind, and solar energetic particles. The most recent assessment of the Ne abundance in the Sun is obtained from measurements of Ne/O in the solar corona and from energetic particles is $A(\mathrm{Ne}) = 7.84$ (Asplund et al. 2005). The solar value according to Lodders (2003) is just slightly higher [$A(\mathrm{Ne}) = 7.87$].

The neon abundances derived here for a sample of early-type stars in the Orion association are found to be quite homogeneous. The average neon abundance for the studied stars [$A(\mathrm{Ne}) = 8.11 \pm 0.04$] is higher than the quoted solar value by ~0.3 dex. In Figure 2 we show our Ne results versus oxygen abundances. The average oxygen abundance for the sample Orion stars is $A(\mathrm{O}) = 8.70 \pm 0.09$, which is entirely consistent with a single oxygen abundance and agrees with the solar abundance of $A(\mathrm{O}) = 8.66$ (Asplund et al. 2005).

Recent results from detailed calculations of oxygen abundances in a sample of three B0.5 V stars in the Orion Nebula indicate an average oxygen abundance of $A(\mathrm{O}) = 8.63 \pm 0.03$ (Simón-Díaz et al. 2006). The oxygen abundance data presented here is a subsample of the stars analyzed in Cunha & Lambert (1994). For the full sample with 18 stars, this previous study obtained an oxygen abundance spread that was larger, $A(\mathrm{O}) = 8.72 \pm 0.13$, but marginally within the abundance uncertainties. Our target stars in this study, however, span a tighter range in oxygen abundances [$A(\mathrm{O}) = 8.70 \pm 0.09$] and are considered to represent a single oxygen abundance for all purposes. Therefore, the B stars in the Orion association can be represented by a Ne/O ratio of 0.26, which is higher than the currently adopted solar value of 0.15 (Asplund et al. 2005).

The Orion Nebula has been the most extensively studied galactic H II region and is recognized as the standard reference for nebular abundance studies in the Galaxy. Recently, Esteban et al. (2004) conducted a careful emission line study of several elements in the Orion Nebula and obtained $A(\mathrm{O}) = 8.65$ and

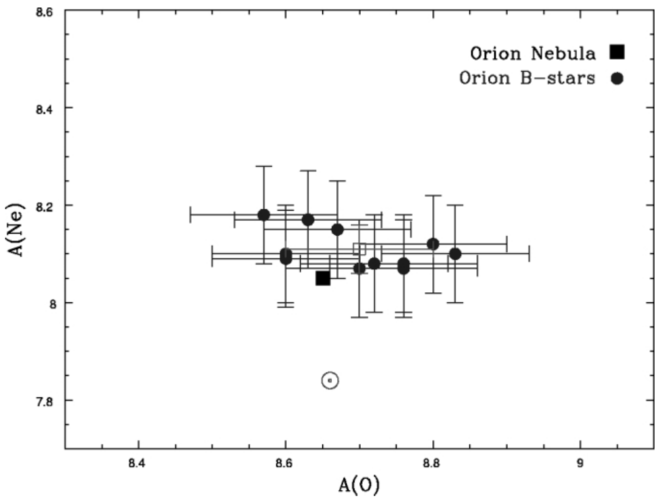

FIG. 2.—Neon abundances derived for the Orion B stars in this study vs. the oxygen abundances from Cunha & Lambert (1994; *circles*). The average Ne and O abundance for the studied sample is represented by the open square. For comparison we also show the currently adopted solar value (Asplund et al. 2005) as well as the H II region abundance obtained for the Orion Nebula by Esteban et al. (2004; *square*), without accounting for any depletion onto grains. [*See the electronic edition of the Journal for a color version of this figure*.]

A(Ne) = 8.05 (or, Ne/O = 0.25); these are gas abundances and corrections for any element trapped in grains have not been considered. This nebular result is quite compatible within the uncertainties with our average for the Orion stars but higher than the solar value (see Fig. 2).

5. CONCLUSIONS

Measurements of neon abundances in a variety of objects that can help define the uncertain neon abundance in the Sun are potentially of great importance for solar physics. We find the Ne abundance in B star members of the Orion association is significantly higher than the solar value by roughly 0.3 dex (~2 ×). We argue that the Ne abundances measured in young OB stars should be a good representation of the solar chemical composition, as is indicated from the good agreement between the abundances in B stars and Sun for other elements such as C, N, and O. The high Ne abundances obtained here come to the rescue of the solar models that require, according to Bahcall et al. (2005a), an increase in the Ne abundance by ~2.8 ± 0.4. Although the high neon abundances obtained here for the B stars are not fully consistent with the increase in neon that is needed to resolve the solar model problem, they nevertheless can alleviate the problem significantly.

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