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The Ne/O abundance ratio in the quiet Sun

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ABSTRACT

Aims. To determine the neon-to-oxygen abundance in the quiet Sun, a proxy for the photospheric abundance ratio.

Methods. An emission measure method applied to extreme ultraviolet emission lines of Ne IV–VI and O III–V ions observed by the Coronal Diagnostic Spectrometer on the SOHO satellite.

Results. The average Ne/O abundance ratio in supergranule cell centre regions is 0.18 ± 0.05, while in supergranule network regions is 0.16 ± 0.04. A photospheric Ne/O ratio of 0.17 ± 0.05 is suggested, in good agreement with the most recent compilation of solar photospheric abundances, but discrepant with a recent Ne/O ratio derived from stellar X-ray spectra and revised neon abundances suggested from solar interior models.

Key words. Sun: abundances – Sun: photosphere – Sun: transition region – Sun: UV radiation

1. Introduction

Understanding the physical processes through which the Sun gives rise to the light that is vital for life on Earth is a fundamental challenge of astrophysics. The standard models of the Sun's interior had been considered a great success following the resolution of the solar neutrino flux problem (Ahmad et al. 2002), giving excellent agreement with sound speed and density variation in the solar interior deduced from helioseismology (Bahcall et al. 2005a). Recently, however, revisions to the solar photospheric abundances for the elements carbon, nitrogen, oxygen and neon (Asplund et al. 2005a) have led to discrepancies between the models and parameters derived from helioseismology. Adjustments to the solar opacities and element diffusion rates have been ruled out as solutions to this problem (e.g., Badnell et al. 2005; Guzik et al. 2005), and so attention has focussed on the new element abundance values, and in particular the abundance of neon (Antia & Basu 2005; Bahcall et al. 2005b; Drake & Testa 2005).

Unlike other abundant elements, the abundance of neon can not be determined by analyses of the solar photospheric spectrum as no absorption lines of Ne or Ne^+ are found there. Instead, the neon abundance has been inferred indirectly from abundance measurements of solar energetic particles (Reames 1999). In such measurements, the neon abundance is referred to oxygen and it is the downward revision of the oxygen abundance by 0.17 dex that is largely responsible for the change in the neon abundance from $\log A(\mathrm{Ne}) = 8.08$[1] to 7.84 (Grevesse & Sauval 1998; Asplund et al. 2005a). By varying parameters in solar models, Antia & Basu (2005) have suggested that the models and helioseismological observations could be reconciled by increasing the neon abundance up to values $\log A(\mathrm{Ne}) = 8.24$–$8.44$, and further work by Bahcall et al. (2005b) has yielded a value of $\log A(\mathrm{Ne}) = 8.29 \pm 0.05$ to improve agreement. Independently, Drake & Testa (2005) have measured Ne/O ratios in the atmospheres of a sample of active stars giving an average value of 0.52, leading to a neon abundance of $\log A(\mathrm{Ne}) = 8.27$ (assuming the solar photospheric oxygen abundance). Following this last work, it is reasonable to ask what is the Ne/O ratio in the Sun's atmosphere.

The solar atmosphere may not seem a promising place to measure photospheric abundances since many years of measurements have demonstrated non-photospheric abundances in the transition region and corona (see, e.g., Feldman & Laming 2000, for a review). However, the abundance anomalies are found to correlate with the first ionization potential (FIP) of the elements, and neon and oxygen are generally considered as high-FIP elements. In addition, the average quiet Sun does not show the FIP effect (Young 2005), and so derived abundances should reflect the photospheric values.

The present work uses extreme ultraviolet spectra obtained from quiet Sun regions by the Coronal Diagnostic Spectrometer (CDS) on board the SOHO satellite to determine

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[1] On the scale in which $\log A(\mathrm{H}) = 12$.

Table 1. Oxygen emission lines used in the present analysis. Transitions within 0.4 Å are blended in the CDS spectra. Wavelengths are from v5.1 of the CHIANTI database (Landi et al. 2005).

Ion	Transition	λ/Å
O III	$2s^2\,2p^2\;^1D_2$–$2s\,2p^3\;^1D_2$	599.59
O IV	$2s^2\,2p\;^2P_{1/2}$–$2s\,2p^2\;^2P_{3/2}$	553.33
	$2s^2\,2p\;^2P_{1/2}$–$2s\,2p^2\;^2P_{1/2}$	554.08
	$2s^2\,2p\;^2P_{3/2}$–$2s\,2p^2\;^2P_{3/2}$	554.51
	$2s^2\,2p\;^2P_{3/2}$–$2s\,2p^2\;^2P_{1/2}$	555.26
O V	$2s^2\;^1S_0$–$2s\,2p\;^1P_1$	629.73

the Ne/O abundance ratio in the temperature range $4.6 \leq \log T \leq 5.8$ of the Sun's atmosphere. The derived value is considered a proxy of the photospheric Ne/O ratio.

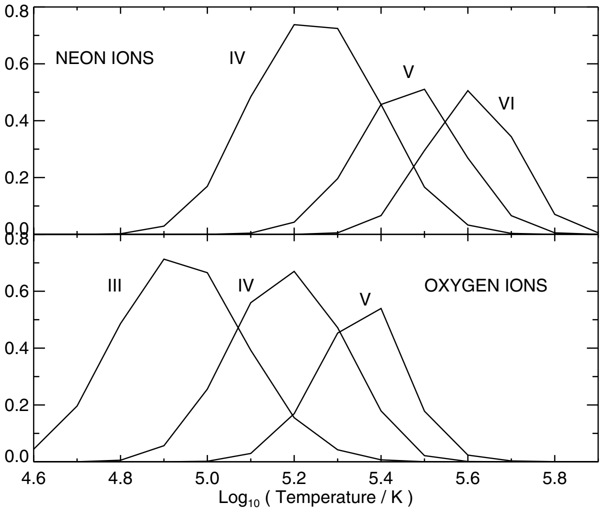

Fig. 1. Ionization fraction curves from Mazzotta et al. (1998) for the neon and oxygen ions.

2. Data

The same data-sets were used for this analysis as for that of Young (2005), i.e., 24 sets of SOHO/CDS spectra obtained over a 28 month period from 1996 March to 1998 June. For each observation, spectra were spatially separated into supergranule network or cell centre regions based on the intensity of the O V λ629.7 emission line. The spectra in each region were then averaged, leading to 24 sets of network and cell centre spectra.

Temperature overlap between the oxygen and neon ions occurs for the ions O III–V and Ne IV–VI seen by CDS (Fig. 1). The atomic transitions and wavelengths of the neon lines were given in Young (2005), while those for the oxygen lines are given in Table 1. The emission line intensities of the neon ions and O V were previously measured by Young (2005), and so only the O III λ599.6 and the four O IV lines were measured here. The four O IV lines are partially blended with each other, and the intensity of the total feature was measured and treated as a single line in the rest of the analysis.

The intensities of the oxygen lines and the Ne VI line were corrected for the narrow slit burn-in caused by degradation of the microchannel plate employed in the NIS detector in the central part of bright emission lines (Lang et al. 2002). Statistical errors from the line-fitting were added in quadrature to relative uncertainty errors in the intensity calibration. The latter vary with wavelength for the different lines from 20% to 29% (Lang et al. 2002).

3. Method and results

Following Young (2005), the variation of plasma with temperature through the solar atmosphere is modelled through discretising the plasma into isothermal regions spaced at temperature intervals of 0.1 dex. The temperature range is chosen to span the regions where the neon and oxygen ions are formed, i.e., $4.6 \leq \log(T/\mathrm{K}) \leq 5.8$ (see also Fig. 1). At each of these 13 temperatures, there is a plasma column depth, h_i (i = 0–12), but only the values of h_i at temperatures $\log(T/\mathrm{K}) = 4.6, 5.2$ and 5.8 (i.e., h_0, h_6 and h_{12}) are allowed to vary. Values of h_i at intermediate temperatures are derived by linear interpolation in the $\log T$–$\log h$ plane during the minimization procedure. In deriving the h_i values, the absolute abundance of one element must be assumed, and I take the new photospheric abundance of oxygen: $\log A(\mathrm{O}) = 8.66$ (Asplund et al. 2005a).

There are thus four parameters – $A(\mathrm{Ne})/A(\mathrm{O})$, h_0, h_6 and h_{12} – to be fit to the six observed oxygen and neon intensities. The line intensities are modelled through Eq. (1) of Young (2005), and atomic data are from v.5.1 of the CHIANTI database (Landi et al. 2005). The minimization procedure of Young (2005) is applied, and the Ne/O abundance ratios for each of the 24 data-sets in the network and cell centre regions are displayed in Fig. 2. The error bars for each point are derived through the χ^2 minimization procedure and are around ±30%, principally arising from the uncertainties in the line intensities.

The statistical average of the Ne/O abundance ratio in the cell centre regions is 0.18 ± 0.01, while in the network regions it is 0.16 ± 0.01. The derived values over the 28 month period are remarkably consistent.

A fixed pressure of $10^{14.5}$ K cm^{-3} was assumed for the analysis (see Young 2005), but assuming a constant density instead does not make a significant difference to the results, as shown in Table 2 where results for densities of 10^9 and 10^{10} cm^{-3} are shown.

Atomic data uncertainties have not been included in the analysis and are likely to be significant, particularly for the ionization fractions of the ions. To investigate the effects of modified ion fractions in a simplistic manner, the analysis was repeated by shifting the ion fractions, F, of only the neon ions forwards and backwards in temperature by 0.1 dex. I.e., $F'(T_i) = F(T_{i-1})$ or $F'(T_i) = F(T_{i+1})$, respectively. The results of this are shown in Table 2, where $F_{\mathrm{Ne}}+$ indicates the neon ions have been moved forward in temperature, and $F_{\mathrm{Ne}}-$ backwards in temperature. The effects are again small, and we use these results to give final error bars of 0.18 ± 0.05 and 0.16 ± 0.04 on the Ne/O relative abundance in cell centre and network regions.

To demonstrate consistency with the analysis of Young (2005), the h_i values from a single data-set are compared with

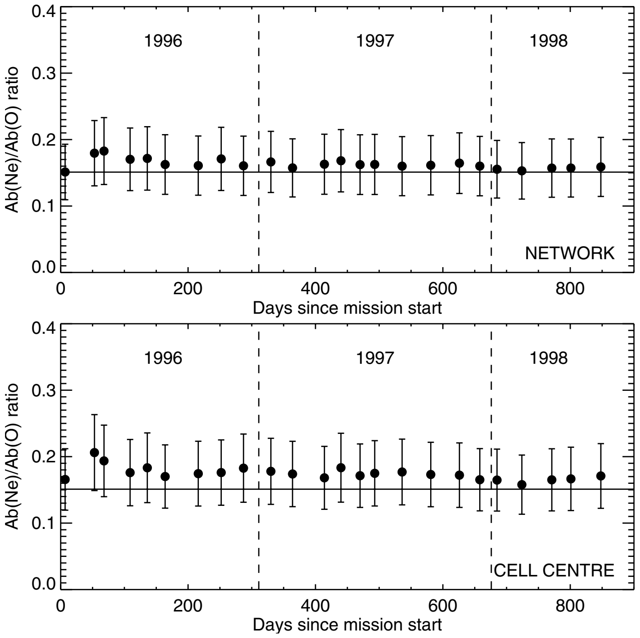

Fig. 2. The derived Ne/O abundance ratios for the network (*upper panel*) and cell centre (*lower panel*) regions as a function of time. The black horiontal line denotes the photospheric Ne/O abundance ratio (Asplund et al. 2005a).

Table 2. A(Ne)/A(O) values derived for different assumptions: fixed pressure, fixed density, and displacements of the neon ion fractions.

	Cell centres	Network
$P = 10^{14.5}$ K cm^{-3}	0.18 ± 0.01	0.16 ± 0.01
$N_e = 10^9$ cm^{-3}	0.19 ± 0.01	0.18 ± 0.01
$N_e = 10^{10}$ cm^{-3}	0.19 ± 0.01	0.18 ± 0.01
$F_{\rm Ne}+$	0.13 ± 0.01	0.12 ± 0.01
$F_{\rm Ne}-$	0.22 ± 0.01	0.20 ± 0.01

those from Fig. 3 of Young (2005) and excellent agreement is found in the overlap region. The column depths from the Ne/O analysis have been scaled downwards by a factor 0.263 due to the different reference abundance used (oxygen in the present analysis, and neon in the Young 2005, analysis).

As a further check on the reliability of the results, the derived column depths were used to predict the intensity of the O VI λ1032 line in cell centre and network regions using atomic data from CHIANTI. Although not observed by CDS, this line was measured by the Harvard S055 instrument on board *Skylab* and Vernazza & Reeves (1978) give average intensities of 474 and 223 erg cm^{-2} s^{-1} in network and cell centre regions, respectively. Averaging the predicted intensities from each of the 24 data-sets here gives values of 487 ± 60 and 211 ± 26, in excellent agreement with the Vernazza & Reeves (1978) values.

4. Discussion

Averaging the derived abundance ratios for the supergranule network and cell centre regions gives a value of A(Ne)/A(O) of 0.17 ± 0.05, in excellent agreement with the ratio of 0.15 ± 0.03 given by the solar photospheric abundance tables of Asplund et al. (2005a). No evidence is found for the enhanced Ne/O abundances found by Drake & Testa (2005) from analyses of X-ray spectra of active cool star atmospheres.

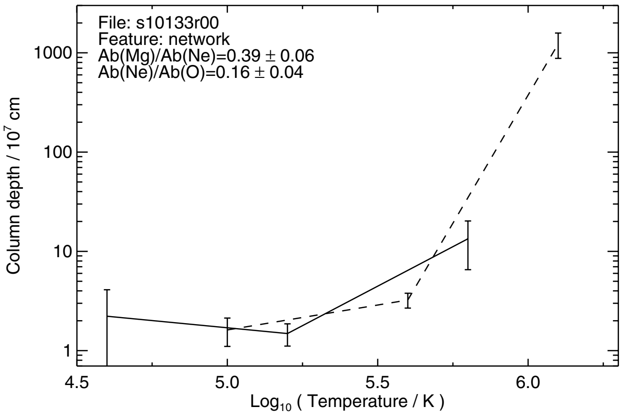

Fig. 3. A comparsion of column depths (h) derived from the present analysis (solid line) with those from Young (2005) (dashed line) for the network spectrum from CDS data-set s10133r00. The curves are scaled to remove the dependence on the reference abundances (see text).

The advantage of studying the quiet Sun is that it is relatively stable compared with the hot active region (likely flaring) plasma that gives rise to the X-ray neon and oxygen lines in active stars. This is reflected in the remarkably consistent value of the Ne/O ratio over the 28 months of CDS observations (Fig. 2). Observations of solar flares have demonstrated Ne/O variations of a factor 2 between different events (e.g., Fludra & Schmelz 1995), while stellar atmospheres show abundance patterns not consistent with the solar corona (e.g., Drake et al. 2001), which could imply as yet unknown processes causing the modifications from the photospheric Ne/O ratios.

Using the photospheric abundance of oxygen from Asplund et al. (2005a) my results lead to a log A(Ne) value of 7.89±0.16 which is in good agreement with the value 7.84 ± 0.06 given by Asplund et al. (2005a), but not consistent with the neon abundances suggested by Antia & Basu (2005) and Bahcall et al. (2005b).

The conclusion from the present analysis is thus that the photospheric abundance of neon is *not* responsible for the discrepancies between standard solar models and helioseismological observations. Further confirmation of this result is provided by Schmelz et al. (2005) who have analysed solar active region spectra from the Flat Crystal Spectrometer flown on board the *Solar Maximum Mission*, while additional arguments for a low neon abundance are given in Asplund et al. (2005b).

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