THE SOLAR BORON ABUNDANCE

J. L. KOHL, W. H. PARKINSON, AND G. L. WITHBROE
Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory
Received 1976 July 22; revised 1976 November 4

ABSTRACT
The first positive evidence for the presence of boron in the Sun is provided by photoelectric measurements of the solar spectrum near 2500 Å. A spectral synthesis analysis of the wavelength region near the $2p^2P_{3/2}^o - 3S_{1/2}$ lines of B at 2496.772 and 2497.723 Å yields the photospheric boron abundance $\log A_B = 2.6 \pm 0.3$ on the scale where $\log A_N = 12.0$. This value, as well as the boron to beryllium abundance ratio (based on the best existing solar beryllium abundance), is in good agreement with predictions of light nuclide formation by galactic cosmic-ray spallation.

Subject headings: Sun: abundances — Sun: spectra

I. INTRODUCTION
This Letter reports the first positive evidence of the presence of boron in the Sun. The chemical abundance of boron in the solar photosphere, $A_B$, is derived from measurements of the solar spectrum near 2500 Å which were made with a rocket-borne high-resolution spectrometer (Kohl and Parkinson 1976). A more complete description of our boron abundance determination, including a description of the measurements at $\mu = 0.23$, will be given in a subsequent paper (Kohl, Parkinson, and Withbroe 1977, hereinafter called Paper II). Earlier work provided upper limits on the solar boron abundance. Grevesse (1968), Wohl (1974), and Hall and Engvold (1975) obtained upper limits for $\log A_B$ of 2.8, 2.3, and 2.25, respectively, based on the absence of infrared B I lines in the photosphere, while Engvold (1970) obtained an upper limit of 2.5 based on the absence of BH and BO from sunspot spectra. All of the above values are on the scale where $\log A_H = 12.0$.

The determination of the solar abundance of boron has important implications regarding the formation of the light nuclides $^6\text{Li}$, $^9\text{Be}$, and $^{10,\text{11}}\text{B}$ in the solar system and in our Galaxy (cf. Trimble 1975). One promising mechanism for the synthesis of these nuclides is the interaction of galactic cosmic-ray protons and $\alpha$-particles with C, N, and O atoms in the interstellar medium (Reeves, Fowler, and Hoyle 1970; Mitter 1970; Menguzzi, Andouze, and Reeves 1971). This mechanism of galactic cosmic-ray spallation predicts a cosmic boron abundance in our Galaxy of $\log A_B = 2.5$ and a $B/Be$ ratio of 10 to 20. These numbers compare favorably with abundances derived for α Lyr by Boesgaard et al. (1974), who found $\log A_B = 2.0$ and $A_B/A_{Be} = 10$. Based on the upper limits to the solar boron abundance given above and the solar beryllium abundance given by Chmielewski, Muller, and Brault (1975), the corresponding values for the Sun would be $\log A_B < 2.25$ and $A_B/A_{Be} < 13$. However, measurements of carbonaceous chondritic abundances imply that the solar system abundances are significantly different, with $\log A_B = 4.04$ and $A_B/A_{Be} = 430$ (Cameron 1973; Cameron, Colgate, and Grossman 1973). The fact that no known process seems capable of making such large amounts of boron (cf. Trimble 1975) suggests that the carbonaceous chondritic boron abundance has been enhanced by some process and is not representative of the primordial material from which the solar system formed (Cameron, personal communication to Reeves 1974).

II. THE MEASUREMENTS
The spectra used in the analysis were obtained with an Ebert spectrometer that had a 75 cm focal length and a 3600 groove mm$^{-1}$ holographically produced grating. The spectrometer was fed by a telescope consisting of an off-axis paraboloid mirror of 93 cm focal length and two plane folding mirrors. The entrance slit was approximately 1.5" by 184". The instrumental profile was measured in the laboratory and is nearly a pure Gaussian with a full width at half-maximum of 0.028 Å. The detection system was photoelectric. Absolute spectral intensities were determined with an uncertainty at ±11%. On 1974 May 15 the instrument was launched at White Sands Missile Range and acquired two spectral scans between 2250 and 3200 Å at the center of the solar disk. Two additional scans were made at the limb at $\mu = 0.23$, where $\mu = \cos \theta$ and $\theta$ is the angle between the normal to the solar surface and the line of sight. H$\alpha$ and Ca K spectropheliograms indicate that the spectra are from extremely quiet regions of the Sun. For more details about the instrument, its calibration, and the observations, see Kohl and Parkinson (1974, 1976).

Figures 1 and 2 illustrate short sections of the spectrum in the vicinities of the B I lines at 2496.772 and 2497.723 Å, respectively. The plotted points are the measurements, and the curves are the results of model calculations discussed below. The plotted points were obtained from point-by-point averages of the two scans from the center of the solar disk. The wavelength scale is based on the laboratory wavelengths (in air) of nearby lines. Deviations from this scale appear to be less than 0.005 Å. The error bars represent one standard
The determination of the photospheric boron abundance is based primarily on the analysis of the Sun center spectrum near the B I line at 2496.772 Å. This is the least blended solar feature for the two B I transitions $2p \ ^2P_{1/2,3/2} - 3s \ ^2S_{1/2}$. Our analysis for the other line at 2497.723 Å provides evidence that supports the abundance value derived from the former line.

The measurements were analyzed using several single-component photospheric models. We report here results obtained with the model of Ayres and Linsky (1976). A discussion of other models will be given in Paper II. Because the spectrum is crowded with spectral lines, we synthesized the spectrum between 2480 and 2540 Å to take into account the influence of the overlapping wings of nearby lines and more distant strong lines. When possible, we used experimental wavelengths and $g_f$-values. Otherwise, the tabulation of Kurucz and Peytremann (1975, hereinafter called KP) was used as a line list. For log $g_f > 1.0$ we used best-fit $g_f$-values that were approximately equal to the tabulated values of KP, but for weaker lines we used the oscillator strength as an adjustable parameter. The van der Waals constants were also adjustable parameters, being increased by up to a factor of 2.5 over classical values in order to obtain better fits to the wings of strong lines. We included all of the normal sources of hydrogen opacity as well as that due to the bound-free absorption from the Mg I $^3P$ level with its ionization limit at 2513 Å (Moore 1949). For the Mg I $^3P$ photoionization cross section we used the value of $45 \times 10^{-18}$ cm$^2$ based on the laboratory measurements of Bottcher (1958).

When all sources of continuous opacity were assumed to be in LTE, the continuum intensity (calculated...
intensity for a given model with no line opacities) at 2500 Å was nearly equal to the observed high points in the Sun center spectrum, but the continuum intensity for the spectrum at $\mu = 0.23$ fell well below the observed high points for all of the usual solar models. It is reasonable to expect the Mg I $3P$ level to be underpopulated with respect to LTE, due to a large photoionization rate near the temperature minimum region, in much the same way as the Si I levels are affected (Vernazza, Avrett, and Loeser 1976). In evaluating the Mg I $3P$ continuous opacity for our spectral synthesis analysis, we introduced departures from LTE in the upper photospheric layers with the approximate height dependence of the $3P$ $5S$ level of Si I (Vernazza, Avrett, and Loeser 1976). The resulting intensities at $\mu = 0.23$ are higher in better agreement with the measured high points.

With the exception of Mg I, all of the calculations were based on the assumption of LTE. A discussion of the validity of our assumption of LTE will be given in Paper II.

We used the turbulence model utilized by Chmielewski, Muller, and Brault (1975) in their analysis of the solar beryllium lines. It is a modified version of Holweger’s (1967) turbulence model and contains a depth-dependent macroturbulence of 1.8 km s$^{-1}$ at small depths and a depth-independent macroturbulence of 0.5 km s$^{-1}$. The calculated spectra were convolved with the known instrumental profile.

To assess the reliability of our analyses of the UV solar spectrum, we compared chromium abundances derived from Cr I lines near 2500 Å and Cr I lines in the visible. Accurate experimental determinations of the gf-values by Huber and Sandeman (1977) were used in the analysis. The values of the chromium abundances derived from the two sets of lines are in good agreement (within 0.2 dex). This supports the reliability of our boron abundance determination.

Figure 1 compares theoretical spectra with the measurements near the B I line at 2496.7717 Å. Each theoretical spectrum was computed with a different boron abundance. The wavelengths of the boron lines were taken from Edlen et al. (1970). Because the isotope splitting is only 0.008 Å (Burke 1955), we did not attempt to determine the $^{10}$B to $^{11}$B abundance ratio. The line at 2496.87 Å was unidentified but was treated as an iron group line with a 1.0 eV excitation potential. The spectral line at 2496.713 Å we attribute to Co I, $b 4P_{1/2} - 4S_{3/2}$ (Russell, King, and Moore 1940). The calculated spectra include the hyperfine structure and wavelengths of this line as derived from laboratory measurements supplied by F. Tomkins and theoretical calculations supplied by W. J. Childs of Argonne National Laboratory. The strength of the Co I line at 2496.713 Å is consistent with that of an unblended Co I line at 2443.55 Å from the same multiplet $b 4P - 4S$ G. The relative gf-values of the two transitions which only differ in total angular momentum quantum numbers $J$ are expected to be very accurate and were taken from the calculations of KP. Based on the cobalt gf-values of KP, the strengths of the Co I lines are consistent with the recent solar cobalt abundance determination of Kerola and Aller (1976).

As is readily apparent the Co I line alone does not account for the observed spectrum at 2496.77 Å. The observed feature is substantially wider and deeper. Introduction of the 2496.772 Å B I line provides a much better fit to the observations. The best fit with the Ayres-Linsky model is obtained with log $A_f = 1.85$. Using the laboratory $f$-value (0.087 ± 0.005) discussed by Kernahan et al. (1975), we obtained log $A_B = 2.6$ on a scale where the logarithmic hydrogen abundance is 12. Use of other recent atmospheric models, turbulence models, and a variety of opacity models yields poorer agreement with the center and limb measurements but the same abundance to within approximately 0.2 dex. Figure 2 compares calculated spectra with the measurements near the B I line at 2497.723 Å. The theoretical spectra are for log $A_B = 0.0, 2.0, 2.6$ and 3.2. This B I line is inherently twice as strong as the other, and it is blended in the solar spectrum by an Fe II line at 2497.714 Å from the $b 3^{2}P_{3/2} - 4^{2}P_{1/2}$ transition (Racah and Shadmi 1959; Roth 1969). As a result, the center of the solar feature near 2497.723 Å is formed high in the solar atmosphere where the assumption of LTE may not hold. However, the parts of the line that are brighter than $9.0 \times 10^{12}$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$ cm$^{-4}$ are formed below $T_{\text{photosphere}} = -2.3$ where LTE is a better approximation. There is a second Fe II transition $b 3^{2}P_{3/2} - 4^{2}P_{3/2}$, with a corresponding solar feature at 2509.123 Å. Laboratory measurements by Crosswhite (1975) were used for the wavelengths and relative strengths of the Fe II lines. A spectral synthesis analysis of the line at 2509.123 Å determined an upper limit on the strength of Fe II 2497.714 Å in the solar spectrum. The resulting calculated spectra of Figure 2 support the abundance value determined from the other B I line.

An error analysis of work such as the present has inherently low confidence limits. We estimate that the most probable uncertainty in the above boron abundance due to uncertainties of random sign in the atmospheric model, spectral synthesis, gf-values, and measuring errors ($±0.1$, $±0.1$, $±0.06$, $±0.1$) is approximately $±0.2$ dex. We made a study of the solar spectrum between 2400 and 2500 Å to determine the likelihood that an unidentified blend would be strong enough to cause a systematic increase in the apparent boron abundance by a significant amount. To affect the boron abundance by 0.2 dex or more would require a spectral line with an intrinsic central intensity of $±1.7 \times 10^{13}$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$ cm$^{-4}$. For the wavelength region studied, there are about eight such spectral features per angstrom, 4.5 of which are tentatively identified. Assuming we would detect the presence of a line within 0.015 Å of a boron line, we would expect (Russell and Moore 1944) $0.2 ± 0.4$ accidental coincidences with the two boron lines.

**IV. CONCLUSIONS**

The abundance of boron in the solar photosphere obtained from the $2p 3^{2}P - 3s 5S$ lines is log $A_B = 2.6$,
and our best estimate of the uncertainty is ±0.3 dex with uncertain confidence limits. The lower limit is just above the upper limit (2.25) of Hall and Engvold (1975). In view of the size of the experimental uncertainties, the difference is not significant. Thus, the actual value may be near the lower limit of our uncertainties, or about log Ab = 2.3.

The solar boron abundance is in excellent agreement with the value of 2.5 predicted by Meneguzzi, Audouze, and Reeves (1971) for their nucleosynthesis model in which Li, Be, and B are produced by cosmic-ray spallation. The solar abundance ratio of B to Be, $14 < A_B / A_{Be} < 56$, obtained from our boron abundance limits and the beryllium abundance value of Chmielewski, Muller, and Brault (1975), is also in good agreement with the spallation model. Our abundance for B is in accord with that obtained for a Lyr

by Boesgaard et al. (1974) and is consistent with the upper limit for the interstellar medium of Morton, Smith, and Stecher (1974).

The authors wish to thank the many people who contributed to this work (a list is given by Kohl and Parkinson 1976). In particular we thank Mr. J. J. Crawford, the project engineer, who made the major contribution to the instrument program. We thank Drs. T. Ayres and J. E. Vernazza for scientific discussions. We are indebted to Dr. W. J. Childs for his calculations of the Co i hyperfine structure and to Dr. F. S. Tomkins for his measurements. We thank Drs. M. C. E. Huber and J. Sandeman for the use of their Cr i gf-value measurements before publication and Mrs. R. Freuder and Ms. P. Wetherbee for their assistance with the data analysis. This work was supported by NASA under grant NGR 22-007-202.

REFERENCES