THE SOLAR ABUNDANCE OF HELIUM DETERMINED FROM A REDSHIFTED PLASMA FLOW OVER A SUNSPOT

J. M. LAMING
SFA, Inc., Landover, MD 20785

AND

U. FELDMAN
E. O. Hulbert Center for Space Research, Naval Research Laboratory, Washington, DC 20375-5230

Received 1993 June 22; accepted 1993 November 4

ABSTRACT

The ultraviolet spectrum of a redshifted plasma flow appearing over a sunspot in data obtained during the NRL HRTS I flight is interpreted as a radiatively cooling plasma. For most lines emitted from this plasma, the assumption of ionization equilibrium during the cooling is good; however, for He II this is not the case. In order to get the helium abundance by comparison with other lines, one must integrate differential equations for the various He ionization fractions, and the temperature, and then calculate the radiation emitted. Our result for the solar helium abundance is in the range 0.078–0.22 relative to hydrogen, with the uncertainty arising from lack of knowledge of model parameters.

Subject headings: Sun: abundances — Sun: UV radiation — sunspots

1. INTRODUCTION

The solar helium abundance is a quantity of extreme importance that so far has eluded direct observation. Its value could be significant in setting limits on the primordial helium abundance, which is a critical test of cosmological models (Olive, Steigman, & Walker 1991) and also has a bearing on the solar neutrino problem (Bahcall & Pinsonneault 1992). Previous determinations of the solar helium abundance have principally been derived from the application of stellar evolution models to the Sun (e.g., Bahcall & Pinsonneault 1992; Bahcall 1989). In these models, the equations of stellar evolution are integrated toward the current age of the Sun, for assumed initial mass fractions of hydrogen (X), helium (Y), and heavier elements (Z). Z remains constant in the solar evolution, and X is iterated until the current observed surface value of \( Z/X \) is achieved. Y is then deduced from the requirement that \( X + Y + Z = 1 \), for either the initial or the current surface values. Other determinations from helioseismology appear to conflict somewhat with one another. The situation is discussed by Kosovichev et al. (1992). The effect of helium diffusion within the Sun on solar oscillation frequencies, and hence on the helium abundance determined by these methods, has been investigated by Christensen-Dalsgaard, Proffitt, & Thompson (1993).

Observations are more difficult to interpret. Measurements of the relative abundances of elements emitted in solar energetic particles (SEPs) or the solar wind generally show that helium is subject to strong abundance variations, related to magnetic structures on the solar surface and processes occurring in the corona (Gloeckler & Geiss 1989). Accordingly, these measurements relate to the helium abundance far away from the solar surface rather than to the photospheric or coronal abundance.

Some of the problems confronting direct observation by spectroscopic techniques have been discussed previously (Laming & Feldman 1992, 1993). Performing the usual emission measure analysis on solar spectra from most regions indicates helium abundances between 5 and 15 times greater than those obtained by assuming simple steady state coronal equilibrium plasma with photospheric abundances (Jordan 1975). This discrepancy has been ascribed to uncertain knowledge of the precise mechanisms and temperature conditions responsible for the excitation of this radiation, but if the decay phase of an impulsive flare can be regarded as being the result of many smaller impulsive events, a model consistent with a helium abundance of about 0.1 can be constructed (Laming & Feldman 1992). In an attempt to find a solar region unlikely to be subject to impulsive heating events, Laming & Feldman (1993) investigated the spectra of a prominence observed by Skylab. The complete interpretation of these data was not possible owing to lack of knowledge of radiation transfer effects in the 1–3\( \mu \)m line, both within the prominence itself and between the solar disk and the prominence, but again a helium abundance of around 0.1 relative to hydrogen was eminently plausible.

Motivated by the difficulties above, we have investigated the spectrum of a redshifted plasma flow appearing above a sunspot in the first High Resolution Telescope and Spectograph (HRTS I) rocket flight data. The redshift is about 80 km s\(^{-1}\), which is sufficient to move the 256 A line in the flow almost completely out of resonance with the unshifted radiation in this line from the solar disk. Thus we are able to neglect excitation of He II by extreme ultraviolet (EUV) radiation. The instrument and the data are described in more detail in the next section.

2. HRTS INSTRUMENT AND DATA

The HRTS (Brueckner, Bartoe, & VanHoosier 1977) instrument is a stigmatic spectrograph. Along the slit direction, the spatial resolution is 0.5–1.0 (0.8 was achieved on the HRTS I rocket flight of 1975 July 21; Brekke et al. 1991), and the spectral dispersion is 4.774 Å mm\(^{-1}\). Spectra are recorded on Kodak 101-01 film, which was then digitized with a PDS microdensitometer. The stigmatic properties of the instrument
mean that each spectral line appears as a patchy image, corresponding to a different spatial region of the Sun. This property is valuable in allowing us to isolate spectra solely from the redshifted plasma blob (spatial extent \( \sim 1' \)) over the sunspot without contamination from nearby but unrelated regions. The spectral regions of interest were scanned with the PDS microdensitometer using a small aperture. Therefore, in order to record the intensity from the entire height of the blob, several scans, each shifted from the previous one by the aperture height, were needed.

Since the investigation described here was only concerned with a small spatial region of the complete HRTS exposures, the only geometrical correction applied was a shift between the top and bottom scans, principally to take out any misalignment in placing the film on the densitometer. Contour plots of the redshifted blob in the light of the \( \text{He} \, \text{II} \, \lambda 1640 \, \text{Å}, \text{C} \, \text{II} \, \lambda 1334 \, \text{Å}, \) \( \text{S} \, \text{IV} \, \lambda 1406 \, \text{Å}, \) and \( \text{N} \, \text{V} \, \lambda 1243 \, \text{Å} \) lines are shown in Figure 1. The contours are labeled with the photographic density they represent multiplied by 10. The heavily and lightly shaded regions show respectively the pixels used for signal and background in

---

**Fig. 1a**—Contour plots of the microdensitometer scans for the lines (a) \( \text{He} \, \text{II} \, \lambda 1640 \), (b) \( \text{C} \, \text{II} \, \lambda 1334 \), (c) \( \text{S} \, \text{IV} \, \lambda 1406 \), and (d) \( \text{N} \, \text{V} \, \lambda 1243 \). The labels on the contours give the photographic density multiplied by 10. The plots in (a), (b), and (c) are from the 51 s exposure, and that in (d) is from the 8 s exposure. The wavelength scale is decreasing toward the right, so the redshifted component appears on the left. The heavily and lightly shaded areas show respectively the pixels taken for signal and background traces to form Fig. 2.

© American Astronomical Society • Provided by the NASA Astrophysics Data System
forming Figure 2 (see below). The first important thing to note is that, when compared with the typical unshifted solar regions, the blob in the He II multiplet at 1640.4 Å is much weaker relative to the blob in other lines (e.g., the C IV doublet at 1550 Å) emitted from the same plasma temperature. Indeed, the general behavior of the stationary component of these lines over the sunspot is not too different from the quiet Sun, but the redshifted plasma is qualitatively different. Some of the redshifted blobs appearing in others of the HRTS flights, e.g., the HRTS II data, do not show such a large difference. They have line intensities and background similar to other solar regions around the sunspot. The redshifted blobs of emission in the HRTS I data are most intense in lines formed at around \(1-2 \times 10^4\) K, falling off markedly for lines formed toward \(10^5\) K, whereas the opposite trend is apparent in the HRTS II observations. The redshifted velocity of the HRTS I plasma blobs remains constant over this temperature range (Nicolas et al. 1982). During the HRTS I rocket flight, some 30 spectra were exposed. The pointing position of the spectrograph on the Sun is known to have changed between some of the exposures. This has been quantified by Bartoe (1977) from an analysis of the Hα images taken by the slit jaws camera. The two spectroscopic filmstrips chosen for the work here were the most intense 51 s exposure and the one immediately following it, an 8 s exposure, in order to get the best traces of intense and weak lines from the redshifted plasma. Between these two, the spec-
The spectrograph did not seem to move along the spectral direction, so the same region of the redshifted plasma has been observed in each case.

The density traces resulting from the microdensitometry were converted to intensity plots using H-D curves generated by standard techniques and the instrument sensitivity calibration of Bartoe (1977). The two-dimensional traces were reduced to one-dimensional plots by summing the two or three most intense pixels in the center of the blob in the spatial direction. The intensity of the stationary line was subtracted from that of the blob by two different techniques. In one case, a straight subtraction of a trace through the line, well away from the blob, from the trace through the blob center was performed. However on some lines, the variation in intensity along the spatial direction makes this inaccurate. In these cases the stationary line was assumed symmetrical, and the blue wing was subtracted from the red wing to leave the blob profile. In most cases, both procedures gave the same results. The subtraction of the blue wing from the red wing is not feasible when the line or the background is asymmetrical, as is...

© American Astronomical Society • Provided by the NASA Astrophysics Data System
the case for He II $\lambda 1640$ (being a multiplet of seven lines) and O v $\lambda 1218$ (since it lies on the wing of Ly$\alpha$, giving an asymmetrical continuum). Traces for the lines shown in contour plots in Figure 1 are shown in Figure 2. The traces include the complete intensity (dotted line), the portion subtracted out (dashed line), and the residual coming from the redshifted plasma (solid line). In these examples, He II and C II were performed by straight subtraction, whereas S IV and N V had their stationary component blue wings subtracted from the red wings. The shaded region indicates the pixels taken in the integration to find the complete emitted intensity in the redshifted component of each line. The resulting intensities for the blob in various lines are given in Table 1. Also given, where appropriate, are the intensities expected per unit emission measure, assuming a steady state plasma in coronal equilibrium, together with the references where the atomic data for these calculations may be found. The intensities per unit emission measure do not include the factor $(n_{\text{He}}/n_e)$ in the expression for the emission measure, since this quantity depends on the helium abundance through the electron density. Hence the emission measures to be presented in Table 2 will be underestimated by a factor $n_{\text{He}}/n_e = (1 + 2 A_{\text{He}}/A_{\text{H}})^{-1}$, where $A_{\text{He}}/A_{\text{H}}$ is the helium abundance relative to that of hydrogen, and it is assumed that the plasma is fully ionized, at least as far as helium. The ionization balance for all cases except for He II (which comes from Laming & Feldman 1993) has been taken from Arnaud & Rothenflug (1985). The intensities (in ergs s$^{-1}$ cm$^{-2}$) for density-sensitive lines have been evaluated for the
electron density appropriate to a constant-pressure atmosphere, with a density of $10^{11}$ cm$^{-3}$ at 9 x 10$^4$ K as indicated by the S iv λ1417/λ1406 intensity ratio (Dufton et al. 1982). From this density determination, we also deduce the column density of the emitting material to be $5.7 \times 10^{15}$ cm$^{-2}$, making the important lines for radiative cooling by elements heavier than and including carbon optically thin. The peak cross section for absorption in the He II 256 Å line will be about $5 \times 10^{-15}$ cm$^{-2}$, leading to an opacity in this line of order unity. Hence in calculating the 1640 Å emission, we assume Case A of Baker & Menzel (1938), i.e., optically thin Lyman lines in He II. We also neglect the absorption of He II 256 Å radiation from the solar disk. The Doppler shift of 80 km s$^{-1}$ will move the absorption line into the wing of the He II 256 Å emission line coming from the solar disk, thereby substantially reducing the absorbed flux in this line, which is likely to be weak directly over a sunspot in any case.

3. INTERPRETATION

Initially it is assumed that the plasma is in coronal equilibrium, and radiatively cooling, and we will proceed to determine the helium abundance based on this. Later it will be

### Table 1

<table>
<thead>
<tr>
<th>Transition</th>
<th>Plate Exposure Time</th>
<th>Intensity (ergs s$^{-1}$ cm$^{-2}$)</th>
<th>Intensity/Unit EM$^a$ (ergs s$^{-1}$ cm$^{-2}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>C II λ1335</td>
<td>51</td>
<td>$5.39 \times 10^2$</td>
<td>$7 \times 10^{-23}$</td>
<td>1</td>
</tr>
<tr>
<td>C II λ1337.5</td>
<td>51</td>
<td>$1.20 \times 10^3$</td>
<td>$1.4 \times 10^{-24}$</td>
<td>2</td>
</tr>
<tr>
<td>Si III λ1206</td>
<td>51</td>
<td>$9.22 \times 10^5$</td>
<td>$1.46 \times 10^{-23}$</td>
<td>2</td>
</tr>
<tr>
<td>He II λ1640</td>
<td>51</td>
<td>$4.02 \times 10^7$</td>
<td>$2.4 \times 10^{-23}$</td>
<td>3</td>
</tr>
<tr>
<td>S IV λ1406</td>
<td>51</td>
<td>$2.49 \times 10^2$</td>
<td>$4.3 \times 10^{-25}$</td>
<td>4</td>
</tr>
<tr>
<td>S IV λ1417</td>
<td>51</td>
<td>$1.26 \times 10^3$</td>
<td>$1.06 \times 10^{-24}$</td>
<td>5</td>
</tr>
<tr>
<td>O III λ1666</td>
<td>8</td>
<td>$1.15 \times 10^4$</td>
<td>$5.28 \times 10^2$</td>
<td>6</td>
</tr>
<tr>
<td>O IV λ1401</td>
<td>51</td>
<td>$5.4 \times 10^3$</td>
<td>$1.49 \times 10^{-24}$</td>
<td>6</td>
</tr>
<tr>
<td>O IV λ1399</td>
<td>8</td>
<td>$8.71 \times 10^2$</td>
<td>$3.06 \times 10^{-25}$</td>
<td>6</td>
</tr>
<tr>
<td>N IV λ1486</td>
<td>51</td>
<td>$1.13 \times 10^4$</td>
<td>$9.4 \times 10^{-25}$</td>
<td>7</td>
</tr>
<tr>
<td>N v λ1238</td>
<td>8</td>
<td>$3.24 \times 10^4$</td>
<td>$1.02 \times 10^{-23}$</td>
<td>8</td>
</tr>
<tr>
<td>N v λ1243</td>
<td>8</td>
<td>$1.64 \times 10^4$</td>
<td>$5.24 \times 10^{-24}$</td>
<td>8</td>
</tr>
<tr>
<td>O v λ1218</td>
<td>8</td>
<td>$6.17 \times 10^4$</td>
<td>$7.8 \times 10^{-24}$</td>
<td>9</td>
</tr>
<tr>
<td>O v λ1371</td>
<td>8</td>
<td>$5.72 \times 10^4$</td>
<td>$1.38 \times 10^{-24}$</td>
<td>9</td>
</tr>
</tbody>
</table>

$^a$ All intensities per unit emission measure quoted are a factor of $n_e/n_p$ too large. This quantity involves the helium abundance, through the ionization of helium increasing the electron density over that which would result from hydrogen ionization alone. The abundances of other elements are too small to be significant here.

### Table 2

<table>
<thead>
<tr>
<th>Transition</th>
<th>DEM$^a$ (cm$^{-3}$)</th>
<th>DEM$^a \times \Lambda$ (ergs s$^{-1}$ cm$^{-2}$)</th>
<th>DEM$^a \times \Lambda \times n_p$ (ergs s$^{-1}$ cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C II λ1335</td>
<td>$7.7 \times 10^{26}$</td>
<td>$9.7 \times 10^4$</td>
<td>$4.3 \times 10^{16}$</td>
</tr>
<tr>
<td>Si III λ1206</td>
<td>$6.3 \times 10^{26}$</td>
<td>$1.3 \times 10^5$</td>
<td>$2.3 \times 10^{16}$</td>
</tr>
<tr>
<td>S IV λ1406</td>
<td>$5.7 \times 10^{26}$</td>
<td>$3.4 \times 10^5$</td>
<td>$3.7 \times 10^{16}$</td>
</tr>
<tr>
<td>O III λ1666</td>
<td>$1.1 \times 10^{27}$</td>
<td>$6.3 \times 10^5$</td>
<td>$6.0 \times 10^{16}$</td>
</tr>
<tr>
<td>O IV λ1401</td>
<td>$3.6 \times 10^{27}/3.9 \times 10^{27}$</td>
<td>$1.9 \times 10^6$</td>
<td>$1.0 \times 10^{17}$</td>
</tr>
<tr>
<td>O IV λ1399</td>
<td>$2.8 \times 10^{27}/2.7 \times 10^{27}$</td>
<td>$1.4 \times 10^6$</td>
<td>$8.0 \times 10^{16}$</td>
</tr>
<tr>
<td>N IV λ1486</td>
<td>$1.2 \times 10^{27}/1.1 \times 10^{27}$</td>
<td>$5.3 \times 10^5$</td>
<td>$3.4 \times 10^{16}$</td>
</tr>
<tr>
<td>N v λ1243</td>
<td>$3.2 \times 10^{27}$</td>
<td>$1.6 \times 10^6$</td>
<td>$8.0 \times 10^{16}$</td>
</tr>
<tr>
<td>O v λ1218</td>
<td>$7.3 \times 10^{27}/3.9 \times 10^{27}$</td>
<td>$2.0 \times 10^6$</td>
<td>$1.3 \times 10^{17}$</td>
</tr>
<tr>
<td>O v λ1371</td>
<td>$3.2 \times 10^{27}/3.4 \times 10^{27}$</td>
<td>$1.7 \times 10^6$</td>
<td>$5.6 \times 10^{16}$</td>
</tr>
<tr>
<td></td>
<td>$1.8 \times 10^{27}/1.9 \times 10^{27}$</td>
<td>$9.2 \times 10^5$</td>
<td>$3.1 \times 10^{16}$</td>
</tr>
</tbody>
</table>

$^a$ All emission measures quoted are a factor of $n_e/n_p$ too small. This quantity involves the helium abundance, through the ionization of helium increasing the electron density over that which would result from hydrogen ionization alone. The abundances of other elements are too small to be significant here.

$^b$ The first differential emission measure relates to constant-pressure cooling, the second to constant-density cooling.
demonstrated that these assumptions alone are inconsistent, since the radiative cooling rate is faster than the recombination rate for certain important ions, most notably He II itself. Possible modifications that would lead to a more physically consistent scenario will be discussed.

The deduced differential emission measures (DEMs) multiplied by \( n_e/n_\text{H} \) following from the assumptions outlined above, are given in Table 2, along with the temperature of formation of each line. In a cooling model the column DEM deduced from such an analysis is modified from the usual definition (e.g., Feldman 1992). The intensity of an emission line is proportional to

\[
I \propto \int G(T) n_e^2 \frac{dS}{dT} dT,
\]

where \( G(T) \) is the temperature dependence of the atomic emission function and \( S \) is the distance through the plasma. By substituting \( dT = -n_\text{e}/n_\text{H} \), \( \Lambda \) is the radiative cooling rate, and elements heavier than helium have been neglected, the intensity becomes

\[
I \propto \int G(T) n_e^2 v \frac{(5/2)(n_\text{e} + n_\text{He} + n_\text{H}) k}{n_\text{e} n_\text{H} \Lambda} \frac{dS}{dT} dT.
\]

For cooling at constant density, the \( 5/2 \) factor in the denominator should be replaced by \( 3/2 \). By analogy with Feldman (1992), the average column DEM for this case is

\[
\left\langle n_e^2 v \frac{(5/2)(n_\text{e} + n_\text{He} + n_\text{H}) k}{n_\text{e} n_\text{H} \Lambda} \right\rangle = \frac{\int G(T) n_e^2 v[(5/2)(n_\text{e} + n_\text{He} + n_\text{H}) k/n_\text{e} n_\text{H} \Lambda] dT}{\int G(T) dT}.
\]

For cooling at constant pressure, the quantity \( n_e^2 v \), which is the total column emission measure in the plasma blob divided by the time taken to cool from its starting to its ending temperature, should be constant with temperature. Thus DEM \( \times \Lambda \times n_\text{H} \) should be approximately constant, assuming small changes in the ionization fractions of hydrogen and helium over the temperature range of interest, and negligible loss of particles from the blob during its cooling through this temperature range. In the case of cooling at constant density, \( n_e \) is also constant with temperature range. In the case of cooling at constant density, \( n_e \) is also constant with temperature, and so the product DEM \( \times \Lambda \) should be constant. Both these quantities are also given in Table 2, where the values of \( \Lambda \) have been taken from Gaetz & Salpeter (1983), whose work is strictly valid only under conditions of ionization equilibrium.

The first assumption (changes in \( f_{\text{HI}} \) and \( f_{\text{HeI}} \)) can easily be checked from the tables of Arnaud & Rothenflug (1985). The second assumption (negligible particle losses from the blob) is applied in view of the following three considerations.

1. All the lines emitted from the blob show the same redshift, regardless of their temperature. Thus any mechanism that scatters particles out of the blob into the ambient medium must not slow the blob up appreciably.
2. If Coulomb collisions between ions within the redshifted plasma and ions in the much less dense (but uniform) surrounding medium are considered as a mechanism for doing this, the problem arises of how the blob is accelerated to \( 80 \text{ km s}^{-1} \) in the first place. Gravitational acceleration would require a free-fall time of \( \sim 300 \text{ s} \), compared with \( \sim 15 \text{ s} \) that the blob spends within view of the spectograph slit. How, then, would the blob survive acceleration to \( 80 \text{ km s}^{-1} \) and then disintegrate as it is observed by HRTS?
3. Other possibilities are plasma instabilities caused by relative motions of ions and electrons. This would be relevant if the blob were accelerated by an electric field and hence carried a current. The blob velocity of \( 80 \text{ km s}^{-1} \) is comparable to the ion thermal velocity (and also the ion sound velocity) at the temperature of the highest temperature lines observed here, making the ion acoustic instability possibly relevant. However, this instability also requires \( T_e \gg T_i \) (electron temperature much higher than the ion temperature, a necessary condition for the existence of ion acoustic waves), and so cannot occur. Assuming the presence of a magnetic field over the sunspot, the ion cyclotron instability should also be considered. Where \( T_e = T_i \) for a hydrogen plasma, Kindel & Kannel (1971) estimate the critical drift velocity to be \( 13\sqrt{2kT/m_e} \text{ km s}^{-1} \). Taking this drift velocity to be \( 80 \text{ km s}^{-1} \) gives a temperature \( T < 2300 \text{ K} \). Assuming ions to be moving in one direction and electrons to be moving in the opposite direction might increase the drift velocity by a factor of 2, and hence the critical temperature by a factor of 4, but over the temperature range under consideration the plasma blob is still stable. As well as possibly scattering particles out of the blob should they occur, the main effect of these instabilities will be to heat the plasma blob, which will have the effect of lengthening the radiative cooling time and also of shutting off the instability itself.

It is also worth mentioning that a presumably tapered magnetic field configuration over the sunspot could lead to something like a magnetic mirror, whereby particles gyrating at larger pitch angles to the field lines will be reflected higher up from the sunspot than those at lower pitch angles. Although this will scatter particles from the blob, it will also alter the redshift velocity in a way not observed in the data.

Although it seems very plausible that \( \text{DEM} \times \Lambda \times n_e^2 \) with \( 0 \leq b \leq 1 \) should be constant, this is not immediately apparent from Table 2. The assumption of constant pressure comes closest to what is expected, but still shows a variation of a factor of \( \sim 3 \) over a temperature range from \( 5 \times 10^4 \text{ to } 2.5 \times 10^5 \text{ K} \), although we feel that this is by far the most likely scenario for a radiatively cooling plasma. We believe that most of this variation arises from uncertainties in the atomic data and/or data reduction. We make the following comments about the spectral lines used in our analysis.

C ii \( \lambda 1335 \).—At the temperature of formation of this line, cooling by hydrogen is important, and hence the same argument about the recombination time as opposed to the cooling time for He II applies here. The recombination time is much longer than the cooling time, hence \( \Lambda \) will be reduced by some as yet unknown amount. Hence the DEM is reliable, but the product \( \text{DEM} \times \Lambda \) is not.

Si iii \( \lambda 1206 \).—Si is a low first-ionization potential (FIP) element, and should show some enhancement over high FIP elements in the solar corona and transition region. However,
over a sunspot the enhancement appears to be diminished somewhat (Feldman, Widing, & Lund 1991). The DEM for Si III in Table 2 assumes a photospheric abundance; this should be considered an upper limit due to the possible abundance enhancement.

O III λ1666, O v λ1371.—The problem with these lines is with the difficulty in adequately subtracting the stationary component and background from the redshifted component, hence the results from the two plates are reported separately. It is possibly fortuitous that the mean of the results for each line agrees quite well with the result from the lines considered reliable. It is also possible that there is a systematic difference between the two plates. However, other lines measured from both plates (N v λ1243, O v λ1218, and O iv λ1399) do not show such a discrepancy, making it hard to draw a firm conclusion.

O iv λ1401.—This line is taken solely from the short-exposure plate (the long exposure was overexposed), and hence might show a discrepancy when compared with He from the long-exposure plate. The 1399 Å line is taken from both plates, which agree with each other. The emission measures derived from these lines are not too discrepant; however, once the quantities involving the radiative cooling rate are formed, it is clear that problems exist. We suggest that the temperature assumed for the formation of this line (1.6 × 10^5 K, the ionization equilibrium temperature of formation) is incorrect, and should in fact be somewhat higher. This would move the DEM into better agreement with those on either side of it (cf. N v and O v) and reduce L.

N v λ1243.—This ion is Li-like, and so has a rather wide contribution function. If substantial emission in this line comes from temperatures higher than the temperature of maximum emission, the product DEM ∝ A will be reduced, since L falls sharply for temperatures increasing above 2.5 × 10^5 K. Neglect of this wide contribution function will lead to an overestimate of DEM ∝ A.

O v λ1218.—This line is in the wing of Lyz, which makes the background subtraction difficult.

An expression for the helium abundance can now be derived. Assuming the case of constant pressure, the value of DEM ∝ n_e for He II is taken to be the mean of those for Si IV and N IV, i.e., (3.55 ± 0.1) × 10^43 s^-1. Including the values of DEM ∝ n_e for Si III, O III, and O v λ1371, i.e., those lines with which there is possibly some uncertainty but which are not clearly unusable, such as C II, O IV, N v, and O v λ1218, gives a mean value (3.8 ± 1) × 10^16, consistent with but much less precise than our previous value. The emission measure is then

\[
\text{DEM} = \frac{3.7 \times 10^{16}}{n_e(A) n_H} \left( q_{\text{H}} + q_{\text{He}} \right),
\]

where \( q_{\text{H}} \) and \( q_{\text{He}} \) are the mean charge states of hydrogen and helium, respectively. This is related to the emission in the 1640 Å multiplet of He II by

\[
\text{DEM} = \frac{I_{\text{obs}}(1640 \text{ Å})}{(I_{\text{1640}/\text{EM}})^2(A_{\text{He}}/A_{\text{H}})},
\]

where \( (I_{\text{1640}/\text{EM}}) \) denotes the energy emitted per atom per unit emission measure. Eliminating the DEM between these two expressions gives a cubic equation for \( A_{\text{He}} \):

\[
\left( q_{\text{H}} + q_{\text{He}} \right)^2 A_{\text{He}} = \frac{I_{\text{obs}}(1640 \text{ Å})}{A_{\text{H}}},
\]

Similarly, expressions for constant density, and for a quasi-steady state case not involving A may also be derived:

\[
\left( q_{\text{H}} + q_{\text{He}} \right) A_{\text{He}} = \left( \frac{I_{\text{1640}/\text{unit EM}}}{1.6 \times 10^{23}} \right),
\]

where the value for \( I_{\text{1640}/\text{unit EM}} = 2.4 \times 10^{-23} A_{\text{He}}/A_{\text{H}} \) is taken from Laming & Feldman (1993). Substituting the observed He II λ1640 intensity of 400 ergs s^-1 cm^-2, and ionization fractions appropriate to 8 × 10^4 K of \( f_{\text{H}} = 1 \) and \( f_{\text{He}} = 1.54 \) (Arnaud & Rothenflug 1985), gives a value for \( A_{\text{He}}/A_{\text{H}} \) of 0.043. This determination may be criticized on the following grounds. Table 3 gives values for the recombination times (Shull & Van Steenberg 1982) and cooling times assuming ionization equilibrium (Gaetz & Salpeter 1983) for the various ions observed by HRTS, at temperatures appropriate to where their emission functions are maximized. It shows that at its temperature of maximum emission the recombination time to form He II is ~25 times longer than the radiative cooling times. Hence, in the absence of any other processes like instabilities discussed above, He II emission cannot be assumed to come for a quasi-steady state plasma, and should really be treated by integrating differential equations for the ionization balance as the plasma cools. These integrations have been performed under constant-pressure and constant-density conditions. The radiative cooling function was assumed to have the form

\[
T > 10^5 \text{ K: } \lambda = 10^{-22} T_6^{-0.7} + 5 \times 10^{-24} T_6^{-0.5},
\]

\[
T < 10^5 \text{ K: } \lambda = 10^{-23.7} T_4^{-2.7} + f_{\text{He}} + \alpha_{\text{He}} E_{\text{He}}
\]

\[
+ 0.1 f_{\text{H}} + \alpha_{\text{He}} E_{\text{He}} + 0.1 f_{\text{He}} + \alpha_{\text{He}} E_{\text{He}} .
\]

The form for \( T > 10^5 \text{ K} \) is an approximation to the curve of Gaetz & Salpeter (1983), which of course assumes ionization equilibrium. For \( T < 10^5 \text{ K} \), our form extrapolates the contribution of Gaetz & Salpeter (1983) for carbon and heavier elements. The succeeding terms represent the cooling coming from radiative recombinations to form neutral hydrogen, ionized helium, and neutral helium, respectively. The \( f_i \) are the ionization fractions for the ions, the \( \alpha_i \) the recombination rates, and the \( E_i \) the ionization energies. Here we assume that every recombination radiates away an energy equal to the ionization

<table>
<thead>
<tr>
<th>Ion</th>
<th>Temperature (K)</th>
<th>( t_{\text{recom, cp}} )</th>
<th>( t_{\text{rad, cp}} )</th>
<th>( t_{\text{rec, cd}} )</th>
<th>( t_{\text{rad, cd}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C II</td>
<td>2.25 × 10^4</td>
<td>0.11</td>
<td>0.11</td>
<td>1.87</td>
<td>1.87</td>
</tr>
<tr>
<td>Si III</td>
<td>5 × 10^4</td>
<td>0.11</td>
<td>0.11</td>
<td>1.87</td>
<td>1.87</td>
</tr>
<tr>
<td>Si IV</td>
<td>6.3 × 10^4</td>
<td>0.13</td>
<td>0.13</td>
<td>1.71</td>
<td>1.71</td>
</tr>
<tr>
<td>He II</td>
<td>8 × 10^4</td>
<td>0.28</td>
<td>0.28</td>
<td>0.76</td>
<td>0.76</td>
</tr>
<tr>
<td>He III</td>
<td>9 × 10^4</td>
<td>0.55</td>
<td>0.55</td>
<td>0.73</td>
<td>0.73</td>
</tr>
<tr>
<td>O III</td>
<td>9.5 × 10^3</td>
<td>0.35</td>
<td>0.35</td>
<td>0.77</td>
<td>0.77</td>
</tr>
<tr>
<td>C IV</td>
<td>10^3</td>
<td>0.71</td>
<td>0.71</td>
<td>0.81</td>
<td>0.81</td>
</tr>
<tr>
<td>O IV</td>
<td>1.6 × 10^3</td>
<td>0.40</td>
<td>0.40</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>N IV</td>
<td>1.6 × 10^3</td>
<td>0.44</td>
<td>0.44</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>N v</td>
<td>2 × 10^3</td>
<td>0.70</td>
<td>0.70</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>O v</td>
<td>2.5 × 10^4</td>
<td>1.10</td>
<td>1.10</td>
<td>2.4</td>
<td>2.4</td>
</tr>
</tbody>
</table>

* In these columns, for the sake of clarity, a helium abundance of 0.1 relative to hydrogen has been assumed. The values for \( t_{\text{recom}} \) are only used to justify the assumption of ionization equilibrium for most elements except helium, and do not enter into any calculations. Constant pressure is denoted by \( t_{\text{rad, cp}} \) and constant density by \( t_{\text{rad, cd}} \).
potential of the ion. In fact recombinations directly to the ground state will radiate away more energy than this, since the thermal energy of the recombining electron must also be included, but recombinations to excited levels will radiate away less energy. In view of the uncertainties in other areas of this work, we feel that extra sophistication here is not really justified. The collisional excitation of these ions is also neglected, since they are formed at temperatures for which $kT$ is very low compared to the excitation threshold. Last, the helium abundance in this expression has been assumed to be 0.1 relative to hydrogen. The results of the integration of the simultaneous differential equations are insensitive to the exact value chosen here. If the other uncertainties in determining the helium abundance in this manner could be controlled, one should in principle integrate until the abundance derived at the end agrees with that put in at this stage.

Once the integrations are performed to find the behavior of the ionization fractions with temperature and time, the emission in the He II 1640 Å multiplet is evaluated. In addition to the constant pressure/density possibilities, we also need to assume a temperature where the cooling stops. It is hard to find a convincing argument for where this should be. We see redshifted emission in the C II lines, so it must cool down to at least $2.25 \times 10^6$ K. The relatively intense lines of O I emitted at

![Graph](image)

**FIG. 3a**

![Graph](image)

**FIG. 3b**

Fig. 3.—Behavior with time of the temperature (dotted line) in $10^6$ K, $n_e^2$ Å (dashed line) divided by 100, and the emission in the He II 1640 Å multiplet (solid line) in photons atom$^{-1}$ s$^{-1}$ (multiply by $7.6 \times 10^{-13}$ to get emission in ergs per unit EM) for radiative cooling at constant pressure from $2.5 \times 10^6$ K to (a) $10^6$ K and (b) $4 \times 10^6$ K. The first, smaller, maximum in the emission rate at about $t = 6$ s corresponds to excitation by electron impacts with already recombined He++. The second corresponds to emission directly following recombination into excited states. The "spike" in the radiative cooling function at this point is something of an artifact due to the analytic parameterization, although there should be a small maximum here. Our interpretations of the results are not affected by this.
$\sim 10^4$ K at $\sim 1304$ Å show no redshifted component. However, estimating the excitation rate from the data given in Judge (1986) suggests that at least an order of magnitude less intensity per emission measure should be present here than for C II, mainly because the Boltzmann factor is substantially reduced by the lower temperature, but the excitation threshold remains approximately the same. Such a low intensity is not clearly detectable on our plates (cf. Fig. 2b), and so we can draw no firm conclusion from the nonappearance of a redshifted component for these lines. Results for constant density and pressure, each for final temperatures of $10^4$ and $4 \times 10^3$ K, these being typical chromospheric and sunspot temperatures, respectively, are shown in Figures 3 and 4. The He II emission behaves in a similar fashion for the two constant-pressure curves. We take the values for $I_{1640}\/\text{unit EM}, n_e \Lambda, f_{\text{He}}$, and $f_{\text{He}}$ corresponding to the peak in the He II emission, which are given in Table 4, and derive helium abundances from equation (7) of 0.078 and 0.22 relative to hydrogen for the $10^4$ and $4 \times 10^3$ K cases respectively. In the constant-density cases the He II emission shows behavior quite different from that for constant pressure, but again the two cases are similar to each other. In these cases there is no temperature or temperature range that can be considered to dominate in the 1640 Å emission. Hence, in order to determine the helium abundance in this case, a complex average over the whole temperature range for the various quantities in equation (8) must be made. We do not attempt this here, since, as discussed above, the cooling is likely to be much closer to constant-pressure conditions, and

---

**Fig. 4a**

**Fig. 4b**

---

Fig. 4.—Same as Fig. 3, but for constant-density conditions. The dashed lines now give $n_e \Lambda \times 10^{10}$. 

© American Astronomical Society • Provided by the NASA Astrophysics Data System
TABLE 4
PARAMETERS FOR HE ABUNDANCE DETERMINATION

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>UNITS</th>
<th>$T_f = 10^4 \text{ K}$</th>
<th>$T_f = 4 \times 10^3 \text{ K}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{1640}/\text{atom}$</td>
<td>ergs s$^{-1}$ atom$^{-1}$</td>
<td>$2.22 \times 10^{-12}$</td>
<td>$5.44 \times 10^{-12}$</td>
</tr>
<tr>
<td>$I_{1640}/\text{unit EM}$</td>
<td>ergs s$^{-1}$ cm$^{-2}$</td>
<td>$2.5 \times 10^{-24} A_{\text{He}}/A_H$</td>
<td>$4.0 \times 10^{-24} A_{\text{He}}/A_H$</td>
</tr>
<tr>
<td>$n_{\text{He}}$</td>
<td>ergs s$^{-1}$ cm$^{-3}$</td>
<td>$12.9$</td>
<td>$98.4$</td>
</tr>
<tr>
<td>$n_e$</td>
<td>ergs s$^{-1}$ cm$^{-3}$</td>
<td>$0.81$</td>
<td>$0.70$</td>
</tr>
<tr>
<td>$A_{\text{He}}/A_H$</td>
<td>cm$^{-3}$</td>
<td>$1.29$</td>
<td>$1.07$</td>
</tr>
<tr>
<td>$9 \times 10^{11}$</td>
<td></td>
<td>$1.4 \times 10^{12}$</td>
<td></td>
</tr>
</tbody>
</table>

in view of the various other approximations made in this work, the level of sophistication required for this averaging is not really justified.

4. DISCUSSION AND CONCLUSIONS

We have determined a solar abundance for helium relative to hydrogen in the range 0.078–0.22, this range being determined by the range of plausible temperatures at which the cooling stops. While not as precise as determinations from solar evolution models (although uncertainties in these arising from questions of helium diffusion and other related thermodynamics are not finalized), we believe that the problems confronting other works (Laming & Feldman 1992, 1993) have been obviated to such an extent that this work qualifies as an "abundance determination," albeit somewhat imprecise, rather than as a "model consistent with a helium abundance of 0.1 relative to hydrogen." The observation of more lines with temperatures of formation around $10^4$ K, i.e., O i, Si ii, etc., would improve the accuracy, both by determining the final temperature and by giving a more precise reference DEM. The treatment of lines from C ii and N v could also be improved to this end. Given the current data, a fundamental limit to how accurately one can determine the intensity of the reprocessed He ii emission is likely to remain.

REFERENCES

Bartoe, J.-D. F. 1977; private communication

© American Astronomical Society • Provided by the NASA Astrophysics Data System