THE SOLAR HELIUM ABUNDANCE IN THE OUTER CORONA DETERMINED FROM OBSERVATIONS WITH SUMER/SOHO

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ABSTRACT

At altitudes of about 1.05 R⊙ or more, the corona above quiet solar regions becomes essentially isothermal. This obviates many of the difficulties associated with the inverse problem of determining emission measure distributions and allows for fairly straightforward relative element abundance measurements. We present new values for the He abundance. The first is based on a reanalysis of the He/O ratio studied previously using data acquired by SUMER. A more thorough evaluation of the atomic physics for He II, including a detailed treatment of radiative recombination, increases the predicted emission in the He II Balmer series compared with earlier analyses. We use a recently revised value of the O abundance to derive an He/H abundance ratio of 0.038 (mass fraction, Y = 0.13), with an error of ~17% coming mainly from the O abundance uncertainty. We demonstrate that this result may be affected by gravitational settling of O relative to He. We also derive an abundance for He by direct comparison with emission lines of the H I Lyman series, with the result He/H = 0.052 ± 0.005 (Y = 0.17), a value similar to He abundances determined in the slow-speed solar wind.

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

1. INTRODUCTION

The firm prediction of the primordial helium abundance has long been considered one of the outstanding successes of big bang cosmology. It comes out in a remarkably robust manner, from the neutron/proton ratio at weak interaction of big bang cosmology. It has long been considered one of the outstanding successes of the standard big bang model of cosmology.

The main sensitivities of YBB are to the neutron half-life (higher value gives weak interaction freezeout at a higher temperature) and the number of light particle species (higher number gives faster expansion rate for a given temperature and hence weak freezeout at higher temperature). This last sensitivity was used by Steigmann, Schramm, & Gunn (1977) to place a limit on the number of lepton generations. Using modern values for the primordial He abundance (YBB < 0.243; Olive & Steigmann 1995) and the baryon/photon ratio in the expressions of Steigmann et al. (1977) gives n_e < 4, in accordance with experiments on the width of the Zα resonance at CERN and the Stanford Linear Collider (SLC).

Helium is of course continually generated in stars as the end product of reactions of the p-p chain. Values for the primordial helium abundance are best determined from metal-poor extragalactic H II regions, where recombination spectra of H I, He I, and He II are visible. Extrapolations of He/H against O/H to zero abundance for O yield mass fractions YBB = 0.232 ± 0.003(σ) ± 0.005(syst.) ≤ 0.243 (Olive & Steigmann 1995). Sasselov & Goldwirth (1995) argue that a more careful treatment of the atomic physics and radiation transfer for the observed recombination spectra could increase YBB to as much as 0.255. The solar system is relatively young at 4.6 × 10⁹ yr, so the helium abundance of the solar protonebula, Y⊙, is expected to be several times 0.01 higher than the primordial value, a value consistent with measurements in the gas planets of the solar system (cf. Niemann et al. 1996; von Zahn & Hunten 1996). It was then something of a surprise when values of the present-day helium mass fraction, Y, determined in the solar convection zone from helioseismology (specifically from the discontinuity in the sound speed at the He ionization zones, where the mean particle mass changes) came out similar to the primordial value. Uncertainties in these techniques stem from the measurement of state and the opacities used for the solar envelope. For instance, Basu (1998) obtains Y = 0.248 ± 0.001 and Y = 0.252 ± 0.001 from OPAL and MHD models using data from the SOI/MDI instrument on SOHO. Kosovichev (1997) has obtained Y = 0.248 ± 0.006 and Y = 0.232 ± 0.006 with the same models, respectively. These and other helioseismology uncertainties are purely statistical, coming from the data inversions. Systematic uncertainties in thermodynamic parameters, e.g., the equation of state, are not accounted for. These results were taken as evidence that gravitational settling of He has occurred within the solar envelope, though note that these measurements are made in the solar convection zone, where substantial gravitational settling seems unlikely to occur. The protosolar He abundance can be determined from solar evolution calculations, including the He settling in the solar radiation zone. The best match to current solar properties (radius, mass, luminosity, etc.) is achieved for a Y⊙ = 0.273 (Bahcall & Pinsonneault 1992), although the inclusion of He settling has a rather small effect on Y⊙. Turk-Chieze & Lopes (1993) calculate a variety of solar evolution models using different opacity databases and treatments of the effects of electron screening on nuclear reaction rates and find 0.2661 ≤ Y⊙ ≤ 0.2762.
2. THE He ABUNDANCE IN THE SOLAR UPPER ATMOSPHERE

The first direct determination of He abundance from solar upper atmosphere (SUA) plasmas was done by Gabriel et al. (1995). They used spectra recorded by the Coronal Helium Abundance Skylab Experiment (CHASE), which was launched into space aboard Spacelab II, to measure the intensity ratio between the H $\alpha$ Ly$\alpha$ 1216 Å and the He $\alpha$ Ly$\alpha$ 304 Å coronal lines, both on the disk and at the limb. The spectrum they used was emitted by a coronal quiet region that extended in height from 45,000 to 135,000 km (1–3) above the limb. By assessing the resonantly scattered components of these lines at the limb, the He abundance value they derived was $Y = 0.23 \pm 0.03$. Resonantly scattered He $\alpha$ $\lambda$304 radiation has also been identified in off-limb observations with the Extreme Ultraviolet Imaging Telescope (EIT) on SOHO (Delaboudinière 1999).

Raymond et al. (1997) used a spectrum emitted by an equatorial streamer at a height of 1.5 $R_\odot$ to determine the coronal He abundance. The spectrum they used was recorded by the Ultraviolet Coronagraph Spectrometer (UVCS) on SOHO. In their analysis they compared the intensity of the He $\beta$ Bay line at 1085 Å with the intensity of an H Lyman line. Unfortunately, the He $\beta$ Bay line was too faint to be detected in their spectra. Therefore, they could establish only the value of 0.048 ($Y = 0.16$) as an upper limit for the He abundance. The upper value of the abundance that Raymond et al. (1997) derived was only 60% as high as the He abundance value that was derived by Gabriel et al. (1995).

In a study on the plasma properties of a quiet-Sun streamer between 1.03 and 1.5 $R_\odot$ that was based on SUMER spectra, Feldman et al. (1998) showed that elemental settling can greatly influence the composition of SUA plasmas. As a result of this study Feldman et al. (1998) postulated that the low value obtained by Raymond et al. (1997) was a result of elemental settling effects that influence plasma compositions at large heights above the solar surface. The same could perhaps to a smaller extent affect the Gabriel et al. (1995) measurements. To minimize the effect caused at large heights by elemental settling, Feldman (1998) used a spectrum that was emitted by plasma located at a height of 1.03 $R_\odot$. In order to improve the statistics of the line intensity ratio Feldman (1998) chose to compare He $\alpha$ Bay $\lambda$1085 intensity with the intensity of the much brighter O vi $2s^22p^2 2P_3/2$ line at 1031 Å. By using the same set of atomic data as Raymond et al. (1997), he found $Y = 0.25 \pm 0.04$. This result was revised in a preliminary version of this work (Laming & Feldman 1999b) to $Y = 0.26 \pm 0.04$.

The He abundance has also been measured in situ from particle measurements made in the solar wind. The fast solar wind that is associated with coronal holes has a quite constant He abundance of 4.8% relative to H ($Y = 0.16$). The slow solar wind, associated with quiet regions, has a slightly lower He fraction (~4%, $Y = 0.14$) but is quite variable (see Feldman et al. 1997; von Steiger, Geiss, & Gloeckler 1997). Some of this variability comes from high-speed streams and their associated magnetic sector boundaries, which can increase or decrease the He abundance, respectively, together with shorter term variations associated with transient phenomena such as flares. Reames, Meyer, & von Rosenvinge (1994) review a large number of these events.

3. SUMER OBSERVATIONS AND ANALYSIS

The SUMER observations analyzed in this paper are described in detail elsewhere (Feldman et al. 1999). Briefly, an equatorial streamer was observed on 1996 November 21/22 during a spacecraft roll maneuver, so that the SUMER slit was oriented in the east-west direction, instead of the usual north-south direction. We focused on the data taken with the 4” $\times$ 300” slit centered at 1160” from solar center, or 1.177 $R_\odot$. The data were flat-fielded and destretched using standard SUMER procedures.

The choice of lines with which to compare the He $\alpha$ emission requires some care. Element abundances in the quiet corona are in general different from those in the photosphere, in that elements with a first ionization potential (FIP) less than about 11.5 eV are enriched by a factor of typically 4, relative to hydrogen, whereas the so-called high-FIP elements (with FIP greater than 10 eV) have no enrichment at all. In coronal hole regions the FIP effect does not appear to operate, and in active regions it may cause intermediate enrichments between 1 and 4. In very old active regions and polar plumes, enrichments of up to 1 order of magnitude or more have been reported, so the best elements for comparison to He $\alpha$ are the high-FIP elements, where no such behavior has been recorded. These elements include N, O, Ne, and Ar.

The most important feature of the abundance determinations of Raymond et al. (1997) and Feldman (1998) is that, at sufficiently high altitudes, the solar corona becomes essentially isothermal. This is important since the He $\alpha$ emission lines are very temperature sensitive at transition region temperatures where their emissivity is maximized but are much less so at coronal temperatures. However, the small fraction of He that retains one electron at the temperature in the more quiescent coronal structures emits sufficient radiation to be measured and compared with other ions formed at coronal temperatures, e.g., O vi.

This isothermal property is demonstrated in Figure 3 of Feldman et al. (1998), which shows the apparent element abundance enhancement over that of oxygen as a function of temperature in the equatorial streamer (the same data as analyzed herein for the He abundance) for high- and for low-FIP elements. In each case the curves overlap close to log $T = 6.15$. In nonisothermal conditions the various intersections between the curves for different ions would appear at widely varying temperatures. A similar plot using lines from various ions of Si from this same data set can be found in Figure 4 of Feldman et al. (1999), giving a temperature of log $T = 6.11 \pm 0.04$. We take this value as the plasma temperature in the analysis that follows. We omitted the curve due to the Li-like ion Si xii from our considerations, since it lies at the extreme short-wavelength end of the SUMER bandpass, where calibration difficulties are suspected to exist (Laming et al. 1997).

3.1. Instrument Issues

The He $\alpha$ Bay multiplet consists of the 2s–5p 1084.913 Å and 2p–5d 1084.975 Å lines. The He $\alpha$ lines appear in close wavelength proximity but separated from several N $\alpha$ lines ($\lambda 1083.990$, 1084.562, 1084.580, 1085.529, 1085.546, 1085.701) that belong to the 2s$^2$2p$^5$ 3P–2s2p$^3$ 3D multiplet. The front mirror of the SUMER telescope is not perfectly
smooth. As a result the intensity of any line recorded above the limb contains a genuine coronal component and a component due to scattered light that originates from emission formed on the solar disk. (For a description of the scattering properties of the SUMER instrument see Feldman et al. 1999). The He II lines that were recorded at a height of 1.03 R⊙ above the quiet limb are no exception. Their intensity needs to be deconvolved to the coronal and scattered components. Figures 1 and 2 show fits to the spectral region and 118 Å. The four peaks fitted to the data are from left to right the N II transitions, the He II line (266 Å), the Balmer γ multiplet, and finally a blend of the N II 1085.53, 1085.55, and 1085.68 Å lines. Figure 1 shows a fit to a spectrum taken from pixels between 88° and 118° from the solar limb, while Figure 2 shows data from pixels between 243° and 273° altitude. In both cases the N II lines are dominated by scattered light. However, the increase in the intensity of the He II multiplet relative to the N II lines in Figure 1 is due to the true coronal emission. The ratio between He II and N II far from the solar limb in Figure 2 was used to assess the contribution of scattered light to the He II observed close to the limb to subtract it from the total emission leaving only the true coronal emission. Fitted intensities for He II and the ratios of these to the total of N II emission for seven positions off-limb are given in Table 1, for each of the two detector positions that recorded these data on the KBr portion of the photocathode. For reference, the results of similar fits to the He II λ992 region, giving the intensities of the He II 992.39 Å (Balmer e) multiplet and its ratio to the nearby N II 991.57 Å line, are given in Table 2. The measured intensity ratio He II λ992/λ1085 is 0.265 ± 0.28, about 1.5σ away from the predicted ratio of 0.315 (see discussion of He II intensities below). In view of the radiative and collisional contributions to the excitation of H I discussed later in this paper and in Raymond et al. (1997), we do not expect any radiative excitation component to the coronal He II emission, so the He II λ992 intensities are not used in further analysis.

![Graph showing intensity vs wavelength](image1)

**Table 1**

| Position (arcsec) | He II λ1085 Intensities |
|------------------|-------------------------|
|                  | He II λ1085         | He II/ N λ1085 |
| 274–304........  | 528.3±4               | 0.241 ± 4.8%  |
| 243–273........  | 597.6                 | 0.265 ± 4.6%  |
| 212–242........  | 689.8                 | 0.276 ± 4.3%  |
| 181–211......... | 777.7                 | 0.285 ± 4.1%  |
| 150–180......... | 920.9                 | 0.322 ± 3.8%  |
| 119–149......... | 1151.6                | 0.357 ± 3.4%  |
| 88–118...........| 1490.1                | 0.389 ± 3.1%  |
| 57–87............| 1818.4                | 0.464 ± 2.8%  |

* Position above limb.
* Measured total counts in the He II λ1085 Å line.
* Ratio of total counts in the He II λ1085 Å line to total counts in the three N II features. Entries give intensity ratio followed by percentage error in this ratio.
* Fluxes in photons s⁻¹ cm⁻² sr⁻¹ are given by counts × 3.183 × 10⁶.

**Table 2**

| Position (arcsec) | He II λ992 Intensities |
|------------------|-------------------------|
|                  | He II λ992         | He II/ N λ992 |
| 274–304........  | 173.7±4              | 0.104 ± 8.0%  |
| 243–273........  | 133.1                 | 0.077 ± 9.0%  |
| 212–242........  | 173.7                 | 0.096 ± 7.9%  |
| 181–211......... | 222.9                 | 0.107 ± 7.1%  |
| 150–180......... | 236.9                 | 0.113 ± 6.9%  |
| 119–149......... | 310.1                 | 0.125 ± 6.0%  |
| 88–118...........| 468.0                 | 0.157 ± 5.0%  |
| 57–87............| 357.5                 | 0.142 ± 5.7%  |

* Position above limb.
* Measured total counts in the He II λ992 Å line.
* Ratio of total counts in the He II λ992 Å line to total counts in the N II λ991.57 Å line. Entries give intensity ratio followed by percentage error in this ratio.
* Fluxes in photons s⁻¹ cm⁻² sr⁻¹ are given by counts × 2.911 × 10⁶.
3.2. The O Abundance and Emission Lines

At the height of 1.03 $R_\odot$, Feldman (1998) assumed that the relative composition between He and O is still photospheric, i.e., no elemental settling effects are as yet at work, and used a value for the oxygen abundance value of log ($\text{O}) = 8.93$ (taken from Anders & Grevesse 1989). The CNO abundances have been recently revised (Grevesse & Sauval 1998), giving a new value of log ($\text{O}) = 8.83$, a decrease of 26%. Thus, in comparison with this the He abundance of Feldman (1998) should be revised downward to 0.06 by number relative to hydrogen, giving a mass fraction $Y = 0.21$. The uncertainty in this new oxygen abundance is given by Grevesse & Sauval (1998) as 0.06 dex, or $\pm 15\%$. As we shall see below, this is likely to be the limiting accuracy in determining the He abundance relative to O.

The pixel range over which the O vi line intensities were integrated is given in the first column of Table 3. The intensities measured for the O vii $1031.93$ and $1037.60$ Å lines are given in the next two columns of Table 3. We assume that these lines are optically thin high in the corona. The intensity ratio $R$ between them is given in the fourth column. Under conditions of pure collisional excitation this ratio should be equal to 2, and its increase from this value gives an indication of how much of the O vii intensity is radiatively excited. The fraction of the O vii $1031.93$ Å line that is radiatively excited is given in the fifth column, and the sixth column gives intensity ratios for He ii $\lambda1085$/O vii $\lambda1031$, for the positions off-limb where a meaningful value can be derived. These ratios have been corrected for the slightly different spectrometer sensitivities at the two wavelengths. The apparent increase in the abundance ratio He/O with height above the limb is immediately suggestive of gravitational settling, which would deplete O relative to He. Since it is apparent that the SUMER destretching procedures do not necessarily map exposures taken on different detector positions to exactly the same pixels, we have decided to leave out data taken from the extreme ends of the detector. For example, note the relative intensities between He ii $\lambda1085$ and 992 at the two lowest altitudes reported in Tables 1 and 2. Another rationale is that the isothermal condition of the solar corona necessary for our analysis is more likely to break down at lower altitudes. As a result our lowest measured position was chosen to be at $88^\circ$–$118^\circ$, a position that is higher than the one measured by Feldman (1998). At this position, the He/O ratio is still higher than that measured by Feldman (1998).

3.3. Atomic Physics Issues

Feldman (1998) used the same atomic data for the O vi and He ii transitions as did Raymond et al. (1997). While the O vi rates are straightforward and uncontroversial, those for He ii require more attention. Very few calculations available treat the necessary electron energy region in the excitation process to be relevant to coronal He ii emission. Raymond et al. (1997) used He ii collision strengths taken from close-coupling approximation calculations (B. M. McLaughlin 1996, private communication). These calculations included levels only up to $n = 3$, so rates were scaled according to the absorption oscillator strengths to get results for the $n = 5$ excitation. A correction for the assumed population by cascades of $+20\%$ was also included. A particular subtlety of neutral or singly ionized atom excitation is that, in general for electron impact energies above the ionization threshold, the ionization channel must be explicitly included in the calculation to get the excitation cross sections right. The reason for this is that the sum of all transition probabilities cannot be greater than unity, but if a physically significant process is left out of the calculation, this unitarity bound cannot be guaranteed. Thus, the He ii data used by Raymond et al. (1997) for collisional excitation are likely to be overestimates of the true excitation rates.

We have recently compiled a model He ii ion using electron impact cross section data calculated by Bray et al. (1993). These authors included a full treatment of electron impact ionization, for excitation from the ground state to levels up to $n = 4$, and electron energies up to 700 eV. We scaled their rates for $n = 4$ by the absorption oscillator strength to get impact excitation rates going up to $np$ states and by $1/n^6$ for $ns$ and $nd$ states. Proton excitation rates among the $n = 2$ levels are taken from Zygelman & Dalgarno (1987), and these results are scaled for proton rates among $n = 3$ and higher levels. Radiative decay rates for E1 transitions were calculated from the expression in terms of hypergeometric functions given in Bethe & Salpeter (1957), and those for the 2E1 transition are taken from Drake & Goldman (1981). We also include radiative recombination into all states of He ii from the bare charge state, calculated using a subroutine due to D. G. Hummer (cf. Hummer &

\[
\begin{array}{cccccc}
\text{Position}^a & \text{O vi } \lambda1031.93 & \text{O vi } \lambda1037.60 & \text{Ratio, } R^b & \frac{2R - 4}{R} & \frac{l(\text{He ii } 1085)}{l(\text{O vii } 1031.93)} \\
\hline
274–304 \ldots & 58588^d & 26273^d & 2.230 \pm 0.74\% & 0.206 & \ldots \\
243–273 \ldots & 87624 & 37619 & 2.329 \pm 0.62\% & 0.283 & \ldots \\
212–242 \ldots & 128668 & 56892 & 2.262 \pm 0.50\% & 0.232 & \ldots \\
181–211 \ldots & 212679 & 94810 & 2.243 \pm 0.39\% & 0.217 & \ldots \\
150–180 \ldots & 366531 & 161865 & 2.264 \pm 0.30\% & 0.233 \pm 2\% & 8.70 \times 10^{-4} \pm 13\% \\
119–149 \ldots & 577583 & 254678 & 2.268 \pm 0.24\% & 0.226 \pm 1.7\% & 7.51 \times 10^{-4} \pm 10\% \\
88–118 \ldots & 922039 & 436193 & 2.114 \pm 0.18\% & 0.108 \pm 3.3\% & 7.03 \times 10^{-4} \pm 7\% \\
57–87 \ldots & 977680 & 451582 & 2.165 \pm 0.18\% & 0.152 & \ldots \\
\end{array}
\]

\footnotesize
\begin{itemize}
\item $^a$ Position above limb.
\item $^b$ Entries give intensity ratio followed by percentage error in this ratio.
\item $^c$ Fraction of $\lambda1031.93$ intensity resulting from radiative excitation.
\item $^d$ Fluxes in photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$ are given by counts $\times 2.889 \times 10^6$ for $\lambda1031.93$ and counts $\times 2.892 \times 10^6$ for $\lambda1037.60$.
\end{itemize}
Storey 1987). This last process produces substantial population in excited levels, so we investigated various sizes of model ion. We base our results (given in Table 4) on calculations including levels up to \( n = 20 \) in He II, i.e., 400 levels in total, plus one for the bare charge state, giving a 401 \( \times \) 401 matrix to invert. The ionization rate between He II and the bare charge state is taken from Arnaud & Rothenflug (1985). Going up to \( n = 30 \) (901 levels) produced further corrections of order 0.5% or less to calculated line emissivities. The density is taken to be \( 10^8 \text{ cm}^{-3} \), as determined from Figure 5 in Feldman et al. (1999) from the Si viii lines. Variations in density of up to a factor of 2 (i.e., much larger than the uncertainty in the plot in this last reference) produce changes in the theoretical emissivities of less than 1%.

The inclusion of radiative recombination produces significant extra emission in lines of the He II Balmer series, leading to an overall lower value of the He abundances than derived in our earlier papers (Laming & Feldman 1999b; Feldman 1998), where this process was not included in the analysis. Table 4 should also be considered as superseding Table 6 in Laming & Feldman (1999a). We checked our results against case A recombination spectra for a temperature of 30,000 K tabulated by Clegg et al. (1999; this is the highest temperature they consider). To simulate a photoionization-recombination equilibrium the ionization rate in our runs at this temperature was increased by a large factor to put essentially all the helium into the bare charge state. Our results in this case were consistently around 6% lower than those of Clegg et al. (1999), for a variety of emission lines and densities, which presumably stems from different choices for atomic data. Our new He II emissivities and those for O vi given as a function of temperature by Laming & Feldman (1999b) give an intensity ratio for He II \( \lambda 1085 \)/O vi \( \lambda 1032 \) of \( (1.59 \pm 0.02) \times 10^{-3} \) for a temperature of log \( T \) = 6.11 \( \pm \) 0.04, using the O and He photospheric abundances from Grevesse & Sauval (1998; 8.83 and 10.93, respectively). When compared with the results in Table 3, this indicates He underabundance relative to O by factors of 0.45 \( \pm \) 0.04, 0.47 \( \pm \) 0.05, and 0.54 \( \pm \) 0.07. The small decrease with height of the above ratio is consistent with a depletion of O relative to He by gravitational settling as mentioned previously. Expressed relative to H the He abundance from the lowest altitude studied is 0.038 \( \pm \) 0.007 where the 8% measurement error and the 15% uncertainty in the O abundance have been added in quadrature.

### 3.4. The He Abundance Measured Relative to H

Lines of the H I Lyman series are also visible in our SUMER spectra. Far from the limb these are dominated by scattered light from the disk, but for the lowest altitude position considered (88”–118”) some true coronal H I emission is detectable. We subtract off the scattered light component using the same ratio determined from the N II and N III lines in the He II fits, whereby the scattered light at position 88”–118” is a factor of 1.825 \( \pm \) 4% more intense than that at 243”–273”. Feldman et al. (1999) have shown that the gross features of the scattered light are essentially independent of wavelength. However, at the few percent level at which we need to work, we did see a variation in the decrease in the scattered light moving away from the limb, with shorter wavelengths (e.g., C III \( \lambda 977.02 \)) decreasing less fast than longer wavelengths (e.g., Si III \( \lambda 1113.22 \)). We therefore found that insignificant improvement in the subtraction of scattered light was to be found by considering more lines than just the two most optimum N II and N III features mentioned above.

From the relative intensities of the Ly \( \beta \) \( \lambda 1025.72 \) and the Ly \( \gamma \) \( \lambda 972.54 \) we are able to calculate the contribution of radiative excitation to each line. A model H I atom identical in all respects to that for the He II ion was compiled using electron impact data from Bubelev et al. (1995). Proton rates for this model come from a code described in Laming et al. (1996), originally applied to the 2s–2p proton excitation of Li-like ions. Results from this code for He II are in good (i.e., \( <20\% \)) agreement with the results of Zygelman & Dalgarno (1987). The ionization rate between H I and the bare charge state is taken from Scholtz & Walters (1991). Again, in checks against Clegg et al. (1999) at 30,000 K a consistent underestimate of around 6% was found, suggesting that, in forming the ratio of emission He II/H I, these deviations from Clegg et al. (1999) will cancel allowing us to compute a theoretical line ratio with very high accuracy. Emissivities for the Lyman series of H I from this model are given in Table 5, again for an electron density of \( 10^8 \text{ cm}^{-3} \). The He II emissivities are as independent of density in this range as the H I results. At log \( T \) = 6.11 \( \pm \) 0.04 the ratio of Ly \( \gamma \)/Ly \( \beta \) is predicted to be 0.336 \( \pm \) 0.002. Taking the ratio of disk intensities of these two lines from the scattered light

| Table 4 | Theoretical He II Emissivities* |
| --- | --- |
| \( \log (T) \) | He II \( \lambda 1640 \) | He II \( \lambda 1085 \) | He II \( \lambda 992 \) |
| 5.4... | 7.46(−15) | 5.66(−16) | 1.79(−16) |
| 5.5... | 5.39(−15) | 4.22(−16) | 1.33(−16) |
| 5.6... | 3.34(−15) | 2.76(−16) | 8.65(−17) |
| 5.7... | 2.34(−15) | 2.01(−16) | 6.31(−17) |
| 5.8... | 1.66(−15) | 1.48(−16) | 4.64(−17) |
| 5.9... | 1.18(−15) | 1.08(−16) | 3.40(−17) |
| 6.0... | 8.68(−16) | 8.12(−17) | 2.55(−17) |
| 6.1... | 6.34(−16) | 6.04(−17) | 1.90(−17) |
| 6.2... | 4.60(−16) | 4.45(−17) | 1.40(−17) |
| 6.3... | 3.40(−16) | 3.33(−17) | 1.04(−17) |
| 6.4... | 2.49(−16) | 2.48(−17) | 7.76(−18) |

**Note:** \( a(\lambda) = a \cdot b \).

*Emissivities are in photons H atom \(^{-1}\) s \(^{-1}\) per unit electron density, evaluated for photospheric abundances and an electron density of \( 10^8 \text{ cm}^{-3} \).

| Table 5 | Theoretical H I Emissivities* |
| --- | --- |
| \( \log (T) \) | H I \( \lambda 1215 \) | H I \( \lambda 1025 \) | H I \( \lambda 972 \) |
| 5.4... | 5.95(−14) | 7.06(−15) | 2.38(−15) |
| 5.5... | 4.70(−14) | 5.68(−15) | 1.91(−15) |
| 5.6... | 3.27(−14) | 4.05(−15) | 1.36(−15) |
| 5.7... | 2.48(−14) | 3.11(−15) | 1.05(−15) |
| 5.8... | 1.88(−14) | 2.37(−15) | 7.99(−16) |
| 5.9... | 1.40(−14) | 1.79(−15) | 6.01(−16) |
| 6.0... | 1.06(−14) | 1.36(−15) | 4.59(−16) |
| 6.1... | 7.88(−15) | 1.02(−15) | 3.43(−16) |
| 6.2... | 5.75(−15) | 7.47(−16) | 2.51(−16) |
| 6.3... | 4.19(−15) | 5.44(−16) | 1.83(−16) |
| 6.4... | 2.99(−15) | 3.88(−16) | 1.31(−16) |

**Note:** \( a(\lambda) = a \cdot b \).

*Emissivities are in photons H atom \(^{-1}\) s \(^{-1}\) per unit electron density, evaluated for photospheric abundances and an electron density of \( 10^8 \text{ cm}^{-3} \).
observed between 243° and 273° and scaling by the absorption oscillator strengths, the intensity ratio in pure radiative excitation would be 0.088. The observed ratio, after correcting for scattered light, subtracting off the contributions from the He II Balmer multiplets that are blended with the H I Lyman lines (calculated from the observed intensities of the He II 1085 and 992 Å multiplets), and applying the correction for the wavelength dependence of the spectrometer sensitivity gives an observed Ly\b /Ly\b intensity ratio of 0.248 ± 4%, where the uncertainty is dominated by the subtraction of scattered light. Thus, the collisional c_s and radiative r_s components of Ly\b are related by c_s = r_s × (0.088 − 0.248)/(0.248 − 0.336) = 1.82r_s. Hence, the fraction of Ly\b that is collisionally excited is c_s/(c_s + r_s) = 1.82/2.82 = 0.65, with a probable error of ±0.04. This reduction of the H I line intensities is summarized in Table 6.

The intensity ratio He II λ1085/H I λ1025.72 is then 0.036 ± 9.8%. The theoretical ratio based on an He abundance of 0.085 relative to H (Y = 0.25) is 0.059 ± 0.3%, where the error comes from the uncertainty in the temperature. This yields a measurement of the abundance ratio He/H of 0.052 ± 10% by number or a mass fraction of Y = 0.17 ± 10%. The uncertainty is dominated by the counting statistics and subtraction of scattered light for the He II 1085 Å multiplet and by the determination of the fraction of H I Ly\b that is collisionally excited. The improvement of this last factor in particular requires subtraction of scattered light to very high precision and is likely to be the limiting factor.

4. DISCUSSION AND CONCLUSIONS

Our two measurements of the abundance ratio He/H are affected in opposite directions by gravitational settling (assuming that this affects ions in order of their mass, with O being the most affected and H the least). There are also unknown systematic errors associated with the O VI ionization balance (H I and He II should be much more secure in this respect). Therefore, we discuss the He abundance determined relative to H of 0.052 ± 0.005. This is a 1 σ uncertainty and includes all known sources of error. Thus, barring any problem with the atomic physics input, we may claim to have the most precise measurement of the helium abundance in the solar corona. The result is strikingly close to He abundance measurements in the slow-speed solar wind, especially bearing in mind that this He fraction (~4%) is known to be quite variable. The reason why this result is lower than previous estimates (Feldman 1998; Laming & Feldman 1999b) from the same observations is the inclusion of radiative recombination as a population mechanism in He II and H I. It has a stronger effect on lines of the Balmer series, so the He II λ1085 emissivity is increased more than that for the H I λ1025, leading to a decrease in the inferred He/H abundance ratio. By including a similar correction to the Raymond et al. (1997) measurement an upper limit of He/H less than 0.21 is derived.

Our result also agrees well with the modeled value of the coronal He abundance for steady state conditions given by Hansteen, Leer, & Holzer (1994). These authors also discuss time-dependent solutions, finding enhancements in the coronal He abundance when the coronal temperature and corresponding flux of slow solar wind protons fall below certain limits. This occurs because the proton-He coupling in the solar wind is sufficiently weak that the protons, as they flow out into the solar wind, essentially leave the He behind in the corona. The coronal temperature in our study, log T = 6.11 ± 0.04, is sufficiently low that, according to Hansteen et al. (1994), this ought to be the case here. However, our result for the He abundance is much more consistent with the higher temperature coronal models where Hansteen et al. (1994) find steady state solutions. Further work (Hansteen, Leer, & Holzer 1997) has investigated the role of chromospheric mixing processes on the coronal and solar wind He abundances.

Various other authors have suggested that the helium abundance could vary in different solar regions. In a model to explain the observed preferential acceleration of 3He in impulsive solar flares, Fisk (1978) found that the necessary electrostatic ion cyclotron waves were more efficiently excited in plasma by electron drifts where the He abundance was increased from its usual value by a factor 2–3 or more. More recent work on this phenomenon appears to have obviated the need for an increased He abundance (cf. Steinacker et al. 1997; Miller 1998, and references therein) in the flare plasma by replacing the electron drift in Fisk’s work with a flare-accelerated electron beam. In a review of available measurements and models Drake (1998) concluded that He abundance enhancements on the order of a factor of 2 over photospheric values could not be excluded among different regions of solar and stellar coronae. This work was primarily concerned with observations of thermal bremsstrahlung continua in stellar coronae that appear to be too intense for a hydrogen-dominated corona, where an increase in the coronal He abundance would go some way to alleviating this difficulty. Share & Murphy (1998), studying gamma-ray spectra observed by the Solar Maximum

### TABLE 6

| Comment | Position* (arcsec) | Ly\b | Ly\b | Ratio β/γb |
|---------|------------------|------|------|------------|
| Total counts ............................................... 88–118 | 56573 ± 0.4% | 13809 ± 0.9% | ... |
| Total counts (assumed pure scattered light)........... 243–273 | 17074 ± 0.8% | 4209 ± 1.5% | 0.251 ± 1.7% |
| Scattered light ............................................ 88–118 | 31160 ± 1.8% | 7681 ± 4% | ... |
| Subtract scattered light ................................... 88–118 | 25413 ± 2.4% | 6127 ± 3.1% | ... |
| Subtract He II ................................................ 88–118 | 25110 ± 2.4% | 6116 ± 3.1% | 0.248 ± 4% |

* Position above limb.

b Entries give intensity ratio followed by percentage error in this ratio.

3 Fluxes in photons s⁻¹ cm⁻² sr⁻¹ are given by counts × 2.948 × 10⁶ for λ972 and × 2.890 × 10⁶ for λ1025.

4 Ratio of disk intensities, includes correction for instrument sensitivity.

5 Ratio of coronal intensities, includes correction for instrument sensitivity.
find isothermal conditions (Li et al. 1998). For the streamer under study in this paper, we still favor conclusions drawn from SUMER observations over those from the \textit{Yohkoh} \textit{SXT}, since the \textit{SXT} data consist of ratios of count rates in two filters, the AlMg and Al filters, not actual spectra, and the strongest lines transmitted by these filters (e.g., O vii, O viii, Fe xvii) originate from higher temperatures than those present in the equatorial streamer. We determine the temperature from a range of Si ions (see Fig. 5 in Feldman et al. 1999) whose temperatures span a more relevant range for this purpose. Of course our abundance determinations use ions usually formed at much lower temperatures than those present in the streamer, but these are hydrogenic ions for which atomic processes can be calculated with very high accuracy.

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