NON-LTE MODEL ATMOSPHERES FOR LATE-TYPE STARS. II. RESTRICTED NON-LTE CALCULATIONS FOR A SOLAR-LIKE ATMOSPHERE

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ABSTRACT

We test our knowledge of the atomic opacity in the solar UV spectrum. Using the atomic data compiled in the first paper in this series from modern, publicly available databases, we perform calculations that are compared with space-based observations of the Sun. At wavelengths longer than about 2600 Å, LTE modeling can reproduce quite closely the observed fluxes; uncertainties in the atomic line data account fully for the differences between calculated and observed fluxes. At shorter wavelengths, departures from LTE appear to be important, since our LTE and restricted non-LTE calculations differ. Analysis of visible/near-IR Na I and O I lines, two species that produce a negligible absorption in the UV, shows that observed departures from LTE for these species can be reproduced very accurately with restricted (fixed atmospheric structure) non-LTE calculations.

Subject headings: line: formation — radiative transfer — stars: atmospheres — Sun: abundances — Sun: UV radiation

1. INTRODUCTION

Understanding the solar UV spectrum and its variability has broad multidisciplinary interest. First, it is closely connected to life on Earth. UV radiation damages DNA, can cause mutations, and may affect the Earth’s climate (Coohill 1996; Larkin, Haigh, & Djavidnia 2000). The UV spectrum of late-type stars also has extraordinary repercussions for the study of larger astronomical objects. Late-type stars have very long lifetimes, which makes it possible to use their photospheric abundances to trace the chemical evolution of the Milky Way. Many heavy elements, such as Ge, Au, Ir, Pt, or Pb, do not produce detectable features in the optical window but have strong lines in the UV (see, e.g., Sneden et al. 2000). The same problem afflicts the light elements B and Be (see, e.g., García López 1996). In an extragalactic context, understanding the formation of the UV spectrum of late-type stars is important because late-type turnoff stars dominate the rest-frame mid-UV spectrum of intermediate-age stellar populations. Dating an unresolved stellar system becomes then equivalent to determining the mean effective temperature of the turnoff stars (Heap et al. 1998). Interestingly, for intermediate and high redshifts, the rest-frame UV is observable from Earth in the optical and near-IR. The age of a galaxy determined from a spectroscopic analysis can be in serious error if the formation of the near-UV spectrum of late-type stars is not understood properly.

As astronomers realized the important role of near-UV stellar fluxes in so many different astrophysical contexts, a controversy arose about how well classical model atmospheres and available atomic data are able to reproduce observations. Inconsistencies between observed and computed solar fluxes were early reported by Houtgast & Namba (1968), Labs & Neckel (1968), Matsushima (1968), and Chmielewski, Brault, & Müller (1975). Missing line opacity was commonly suggested as the origin of the discrepancy (Holweger 1970; Vernazza, Avrett, & Loeser 1976). Dragon & Mutschlecner (1980), Kurucz & Avrett (1981), and Kurucz (1992) included millions of atomic and molecular lines previously ignored in the computations and claimed to have solved the problem. However, Bell, Paltoglou, & Tripicco (1994) criticized the suggested solution, since high-dispersion solar spectra in the regions of 3400–3450 and 4600–4650 Å revealed that the synthesis based on Kurucz’s line list predicted many absorption lines that were not observed. Bell et al. (1994), and later Balachandran & Bell (1998) and Bell, Balachandran, & Bautista (2001), proposed missing contributors to the continuum absorption (in particular, a larger Fe I photoionization cross section), rather than line blanketing, as the most likely explanation.

The controversy continues, and the existence of a missing UV opacity has also been discussed in many stellar studies. Malagnini et al. (1992) and Morossi et al. (1993) compared observations and Kurucz’s calculations for late-G and early-K stars, finding that theory underpredicted the observed near-UV fluxes. Other authors have apparently not found such inconsistencies in the analyses of late-type, metal-poor stars or early-type stars (Fitzpatrick & Massa 1999; Allende Prieto & Lambert 2000; Peterson, Dorman, & Rood 2001).

In Allende Prieto et al. (2003, hereafter Paper I), we presented a new set of model atoms for use in non-LTE (NLTE) calculations that are based on harvesting modern databases following a set of uniform criteria. We use the new model atoms here to study the sources of opacity in the
near-UV spectrum of the Sun and take a fresh look at the problem of the missing opacity (\$2\). We apply the data to the so-called restricted NLTE problem—the solution of the statistical equilibrium equations adopting a fixed LTE structure—for the solar photosphere, examining the effect of departures from LTE in optical and near-IR oxygen and sodium line profiles in \$3. Section 4 summarizes our results.

2. THE SOLAR NEAR-UV CONTINUUM

To produce a realistic calculation of the solar UV flux is vastly more complicated than doing so at visible or near-IR wavelengths. The penetration of convection into the photosphere results in thermal and velocity inhomogeneities (granulation), whose effect on the spectral energy distribution has never been seriously considered. At wavelengths shorter than 2500 Å, bound-free metal absorption becomes dominant, producing a sharp increase in opacity toward shorter wavelengths as we cross the different metal photoionization thresholds. This is a serious difficulty, since photoionization cross sections for metals are not as well determined as for H or H\(^+-\). Line absorption becomes a very important contributor at shorter wavelengths, introducing an additional obstacle to accurate modeling because of the limited availability and quality of the required atomic data. Finally, the increase in opacity shifts the formation region to higher atmospheric layers, where the density is low, and spatial (and time) inhomogeneities appear to be significant. This last difficulty may be so serious that most of the assumptions adopted in photospheric models could break down.

Nonetheless, much progress has occurred in the last several years affecting the availability of atomic data, observations, and modeling techniques, and thus it seems appropriate to use new model atoms to update the calculations and compare them with observations. We adopt a fixed atmospheric structure (temperature, electron pressure, and gas pressure as a function of optical depth) calculated assuming LTE, energy and hydrostatic equilibrium, and a plane-parallel geometry. We employ the necessary atomic data (Paper I) together with the hybrid complete linearization/accelerated lambda iteration method (Hubeny & Lanz 1995) to solve the so-called restricted NLTE problem for different species.

2.1. Modeling

Our analysis ignores a number of factors in the modeling that are known to affect the computed fluxes. The adopted values for the mixing-length parameters (see, e.g., Castelli, Gratton, & Kurucz 1997; Barklem et al. 2002) or the adopted solar abundances are two controversial examples. In addition, we neglect molecular opacities, which are known to contribute most at wavelengths shorter than about 2200 Å. To keep the number of variables at a manageable level, concentrating on the effect of the metal opacities, we have chosen to use an LTE model atmosphere interpolated from the grid of Kurucz (1993). The employed grid was calculated for a microturbulence of 2 km s\(^{-1}\) and a mixing length \( \alpha = l/H_P = 1.25 \) with no overshooting. The adopted model is indeed quite similar to the MISS semiempirical model of Allende Prieto et al. (2001a; see Fig. 1), and the calculated fluxes are very close in the wavelengths we are interested in (see below), but the theoretical structure

(1) extends into smaller optical depths and (2) is originally specified in terms of the column density (mass in Fig. 1) rather than optical depths, and therefore we avoid the use of external opacity packages to convert between those two scales. We have adopted a value for the microturbulence of 1.1 km s\(^{-1}\) (Allende Prieto et al. 2001a) and solar abundances from Grevesse & Sauval (1998), unless otherwise specified.

We considered the following species in NLTE: H\(^i\), He\(^i\), Li\(^i\), Be\(^i\), Be\(^{ii}\), B\(^i\), C\(^i\), N\(^i\), O\(^i\), Na\(^i\), Mg\(^i\), Mg\(^{ii}\), Al\(^i\), Si\(^i\), Si\(^{ii}\), Ca\(^i\), Ca\(^{ii}\), Fe\(^i\), and Fe\(^{ii}\). Our model atoms for Fe\(^i\) and Fe\(^{ii}\) are based on the concept of superlevels, described in Hubeny & Lanz (1995; see also Anderson 1989). We considered H\(^-\) opacity, as well as electron scattering and Rayleigh scattering by neutral hydrogen (see Hubeny 1988 for more details). Besides the largely dominant H\(^-\), we found C\(^i\), Mg\(^i\), Al\(^i\), Si\(^i\), Ca\(^i\), and Fe\(^i\) to be relevant for the near-UV continuum of a solar-type star.

Figure 2 shows the normalized difference between the predicted LTE fluxes when only hydrogen (bound-free,
free-free, and bound-bound) opacity is included, \( F(H) \), and with the addition of only one more contributor, \( F(H, X) \), where \( X \) can be \( H^- \) or any of the metals. The graph shows the impact of the different species in such a way that the closer to unity they reach in the plot, the more important their contribution is. The contribution from the metals comes from the bound-free absorption by neutral atoms, mainly from the lowest levels. This comparison shows that besides neutral hydrogen and \( H^- \), only \( Fe \) and \( Mg \) are relevant at wavelengths longer than 2100 Å. \( Al \) becomes important for wavelengths shorter than about 2070 Å. Below that wavelength, the figure is not so informative, as \( H \) loses its dominant role. Figure 3 shows the actual LTE fluxes \( F(H, X) \) excluding (left panel) and including (right panel) metal line opacity, revealing that \( Si \) bound-free absorption becomes significant for wavelengths shorter than about 2000 Å and dominant below \( \sim 1670 \) Å. As discussed below, the photospheric origin of the solar spectrum observed at these and shorter wavelengths is questionable, and the adequacy of the adopted model atmospheres more than doubtful. Our results are in qualitative agreement with previous studies\(^2\) (e.g., Travis & Matsushima 1968; Bell et al. 2001).

2.2. Observations

In the last decade two instruments aboard the Upper Atmosphere Research Satellite (UARS) have provided solar near-UV absolute irradiances with unprecedented accuracy. The Solar-Stellar Irradiance Comparison Experiment (SOLSTICE; Rottman, Woods, & Sparm 1993; Woods, Rottman, & Ucker 1993) has continuously monitored the solar spectrum between 1190 and 4200 Å since 1991 with a resolution of up to 2.5 Å. Flying on the same spacecraft, the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM; Brueckner et al. 1993) has a similar spectral coverage and resolution. Both instruments had preflight calibrations using the Synchrotron Ultraviolet Radiation Facility (SURF II) at the National Institute of Standards and Technology (NIST), but SOLSTICE observes hot stars to track variations in the instrumental sensitivity, whereas SUSIM uses standard lamps and redundant optics for that task.

Additional checks of the absolute solar fluxes measured by these instruments were carried out by comparison with simultaneous measurements with two more instruments, a copy of UARS/SUSIM (SUSIM ATLAS) and the Shuttle Solar Backscatter Ultraviolet experiment, which flew on the shuttle Atmospheric Laboratory for Applications and Science (ATLAS) missions in 1992 March, 1993 April, and 1994 November (Woods et al. 1996). UARS/SUSIM daily solar irradiances (version 20; level 3BS) between 1991 and 1998 are available from the World Wide Web.\(^3\) SOLSTICE daily averaged spectra (version 9; level 3BS) between 1991 and 1996 are also publicly available.\(^4\)

We have combined six spectra obtained by SOLSTICE and UARS/SUSIM during the three flights of the ATLAS mission. The SUSIM spectra were smoothed to the same resolution as the SOLSTICE data by T. Woods and are available from the SOLSTICE Web site.\(^5\) The standard

\(^2\) Comparison with previous works shows that \( Cr \) will also produce a very small (but noticeable in Fig. 2) contribution to the near-UV continuum opacity.

\(^3\) See http://louis14.nrl.navy.mil/susim_uars.html.

\(^4\) Available at ftp://daac.gsfc.nasa.gov/data/uars/solstice.

\(^5\) See http://lasp.colorado.edu/solstice.
deviation of the six, divided by their mean, is shown in Figure 4. These figures provide an order-of-magnitude estimate of the uncertainty in the calibrations and, at short wavelengths, of the level of variability of the solar spectrum in the period bracketed by the observations. For wavelengths longer than about 1800 Å, we can safely compare our calculations with the average spectrum within a few percent. The UARS fluxes are given as irradiance at Earth’s mean distance (1 AU).

The uncertainties in the adopted value for the astronomical unit, the corrections between the position of the observatory and the center of the Earth, and the displacement of the solar center from the Earth-Sun barycenter are small enough to be neglected (Huang et al. 1995; Brown & Christensen-Dalsgaard 1998). The correction of the observed irradiance to determine the flux at the solar surface deserves some comments. A comparison among published measurements of the apparent solar radius between 1980 and 2000 by Golbasi et al. (2001) shows a large scatter. It is unclear whether the listed measurements can be directly compared and which of the employed methods (and definitions) is the more appropriate to use in our case. The many contradictory results in the literature reporting variations of the solar radius with the solar cycle, and on other timescales, alerts us to systematic effects between different experiments (see, e.g., Basu 1998; Antia et al. 2000).

Five average measurements (from three different methods) centered in the years between 1990 and 1995 show relatively consistent results, with an average value $\theta / 2 = 959.492 \pm 0.085$. At the same time, the data suggest a slow decrease in $\theta$ with time, which seems also in agreement with the results of Costa et al. (1999) from radio maps. Conservatively, we adopt an uncertainty for $\theta / 2$ of $0.25\%$, and therefore we correct the observed flux to determine the solar surface flux by applying a factor $(d/R)^2 = 1/\tan^2(\theta / 2) = 46.250 \pm 40$. This factor introduces less than a 0.001% uncertainty in the derived solar surface flux, which is negligible compared to the scatter among the six SOLSTICE/SUSIM spectra. If we use the solar radius derived from the observed p-mode frequencies by Takata & Gough (2001; see also the results from the f-modes by Schou et al. 1997; Antia 1998), we find $(d/R)^2 = 46.240 \pm 19$. A decrease in the total solar irradiance by $\sim 0.02\%$ between 1991 and 1995 has also been reported from measurements from another instrument on UARS, the Active Cavity Radiometer Irradiance Monitor (ACRIM II; Fröhlich 2000). This reduction in the solar irradiance is about 4 times larger than what could be induced by the possible shrinking in $\theta$. If interpreted as a change in the solar effective temperature, such variation would be produced by a decrement in $T_{\text{eff}}$ of less than 2 K.

**2.3. Observations versus Calculations**

Some of our calculations including line opacity employ the line list prepared by R. L. Kurucz and distributed with TLUSTY. A newer line list is available from Kurucz’s Web site. Further tests were carried out with a line list based on a STELLAR request to the Vienna Atomic Line Database (VALD; Kupka et al. 1999; Stempels, Piskunov, & Barklem 2001) for the atmospheric parameters of the Sun. Although the differences were small, we obtained a marginally better agreement with the observations in the 2700–4000 Å region when using the VALD list. Therefore, the VALD list was adopted.

Figure 5 shows our LTE calculation (red line) and the observed spectrum (black line). The overall agreement at wavelengths longer than about 1750 Å is good, especially to the red of $\sim 2700$ Å. With the exception of a few isolated regions, the observed fluxes are closely reproduced. Between 2700 and 4000 Å, the predicted fluxes are an average of 1.8% lower than the observations ($\sigma_{\text{rms}} = 14\%$). If we use the MISS semiempirical model (Allende Prieto et al. 2001a), we find a slightly larger average difference of $7\%$ ($\sigma_{\text{rms}} = 13\%$). At these wavelengths, diatomic molecules may introduce some additional line opacity that we have neglected, but the good agreement that we find with the observed fluxes suggests that this must be very limited. The disagreement found in the shortest wavelengths is not a surprise, since the large increase in opacity at these wavelengths shifts the atmospheric region where the spectrum is formed from the photosphere to the chromosphere. Below $\sim 1600$ Å the continuum is formed at $\tau \lesssim 10^{-4}$. Dragon & Mutschlechner (1980) pointed out that at wavelengths shorter than about 2200 Å, the CO line opacity becomes very important. Our own LTE calculations, including about 400,000 CO transitions with data from Kurucz’s line lists, indicate, however, that CO is only a minor contributor between 1100 and 4600 Å.

In the top panel, in which the agreement is best, a systematic discrepancy is apparent to the red of 4000 Å. The continuum opacity is well determined at those wavelengths, and therefore this might signal problems with the calibration of the observed fluxes in that region—extreme for the discussed instruments. Between 1700 and 2200 Å, the LTE calculation shows better agreement with the observations. This is most likely connected to the photoinization edge of the ground level of Al i. The Al i autoionization line at 1932 Å is predicted in LTE and observed, but it is missing in the NLTE calculation, confirming our suspicions about the NLTE population of the ground state of Al i. Conversely, the NLTE flux is closer to the observations than the LTE calculation for the range 2200–2400 Å. In the middle panel

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6 See http://tlusty.gsfc.nasa.gov.

7 See http://kurucz.harvard.edu.
of Figure 5, the region between 2400 and 2600 Å shows a poor fit, which, from inspection of Figure 3, is probably connected to the photoionization of Mg I. The predicted departures from LTE for the lowest levels of Mg I seem to have the wrong sense in that our NLTE calculation enhances the discrepancy with the observations in this spectral window. Dragon & Mutschlecner (1980) and Kurucz & Avrett (1981) also noticed significant discrepancies between observed and computed fluxes in this region. At 2650–2700 Å the disagreement may also be caused by departures from LTE in neutral magnesium or iron.

It is possible to compare the LTE calculations at very high resolution \((R \sim 5 \times 10^5)\) with the solar atlas of Kurucz et al. (1984) for wavelengths redward of 2960 Å. Figure 6 compares the high-resolution observations in the solar atlas of Kurucz et al. (1984) with the synthesis at a similar resolution between 3000 and 3090 Å. Since the observed spectrum is not in an absolute flux scale, we have normalized the two data sets’ maxima to be 1 in each window. A comparison at lower dispersion is even more relevant for our goals. We have adjusted the observed and calculated spectra in the window 2980–3240 Å by fitting to, and dividing by, a straight line for each of them. Figure 7 shows the corrected fluxes after degradation to a resolution of 2 Å. These figures indicate that excessive line absorption is not covering a lack of continuum opacity. The \(\sigma_{\text{rms}}\) between the two curves in
Fig. 6.—Observed (solid line) and calculated (dashed line) fluxes at very high resolution in the range 3000–3090 Å, fitted to and divided by a straight line derived by least-squares fitting to compare the calculated and real line absorption. The maximum flux has been normalized to 1 for each window. OH lines are not included in the line list used in the spectral synthesis.
we invariably adopt a depth-independent microturbulence model, and, therefore, following Allende Prieto et al. (2001a), described in Paper I. All the calculations were carried out with the model atoms UV flux, and they have essentially no effect on it (see sodium. These two elements are very weakly sensitive to the particular importance in stellar astrophysics: oxygen and absorption in the UV. We have selected two elements with formed for the species that do not produce significant $i$ Mg spectral synthesis in Figure 5, may be necessary to obtain to account for the iron line absorption. Explicit consideration of superlevels in the statistical equilibrium calculations rely on the concept of superlevels to account for the iron line absorption. Explicit consideration of the line absorption, line by line, as we do for the spectral synthesis in Figure 5, may be necessary to obtain realistic NLTE populations for species such as Al i and Mg i.

An independent check of the atomic models can be performed for the species that do not produce significant absorption in the UV. We have selected two elements with particular importance in stellar astrophysics: oxygen and sodium. These two elements are very weakly sensitive to the UV flux, and they have essentially no effect on it (see § 2). All the calculations were carried out with the model atoms described in Paper I.

We aim only at identifying key aspects of the NLTE modeling, and, therefore, following Allende Prieto et al. (2001a), we invariably adopt a depth-independent microturbulence of 1.1 km s$^{-1}$ and a Gaussian macroturbulence of 1.54 km s$^{-1}$. We also remind the reader of the neglect of fine structure in the model atoms, which is likely responsible for small differences between lines of the same multiplet. The spectral syntheses made use of the damping constants for H collisions published by Barklem, Piskunov, & O'Mara (2000), assuming the cross section to be proportional to $T^{	heta/4}$ for all lines. The $f$-values for the discussed lines are well known, as indicated by the quality flag in the NIST database, or adopted from previous works in the literature that are explicitly mentioned in the corresponding sections.

3. THE RESTRICTED NLTE PROBLEM IN THE SOLAR ATMOSPHERE—OPTICAL AND NEAR-IR LINE PROFILES OF O i AND Na i

From our comparison with observed fluxes, we can expect that using a fixed LTE atmospheric structure to solve the level populations of species with an important role at short ($\leq 2000$ Å) wavelengths will be problematic, since the continuum flux is not well matched in that region. We carried out such calculations for Mg i and Al i, finding that the observed line profiles of optical transitions were indeed generally very poorly matched in NLTE, or at least that the NLTE predicted profiles differed more significantly from the observed ones than did the LTE profiles. Our statistical equilibrium calculations rely on the concept of superlevels to account for the iron line absorption. Explicit consideration of the line absorption, line by line, as we do for the spectral synthesis in Figure 5, may be necessary to obtain realistic NLTE populations for species such as Al i and Mg i.

An independent check of the atomic models can be performed for the species that do not produce significant absorption in the UV. We have selected two elements with particular importance in stellar astrophysics: oxygen and sodium. These two elements are very weakly sensitive to the UV flux, and they have essentially no effect on it (see § 2). All the calculations were carried out with the model atoms described in Paper I.

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3.1. Oxygen

The O i triplet at about 7770 Å can be observed in quite different types of stars, and it is the only strong atomic feature produced by oxygen in late-type stellar spectra. Despite the high excitation of this multiplet, NLTE effects are important (e.g., Kiselman 1993, 2001). A recent analysis of the [O i] forbidden line at about 6300 Å, which seems unaffected by departures from LTE, provides a reference abundance that, in addition to the line profiles, may help to validate our NLTE calculations.

There is a controversy as to the importance of hydrogen collisions in the statistical equilibrium of oxygen (e.g., Reetz 1999; Takeda 1994). We carried out some tests with different model atmospheres, finding small but appreciable changes in the predicted lines. We take into account the charge transfer reaction, O + H$^+$ → O$^+$ + H, with the data compiled by Kingdon & Ferland (1996).

Because of the high excitation of the involved terms, one needs a very extended model atom to prevent spurious results in NLTE calculations of the triplet. Our model atom (54 levels and 242 radiative transitions) and the departure coefficients for the lowest six levels of O i are depicted in Figure 8. The lower level of the oxygen triplet ($^5$P$^0$) is overpopulated, while the upper level ($^5$P$^1$) is underpopulated in the line-formation region. Consequently, the line source function drops below the Planck function. This, together with an increased line opacity, will produce deeper profiles. Our results are similar to the calculations described by Kiselman (1993) for a model atom with 44 levels. In contrast to the situation for the infrared triplet, Figure 8 shows that the departures from LTE expected for the two lowest levels ($^3$P$^1$ and $^1$D), which are connected by the [O i] line at 6300 Å, are small in the deep layers where this weak line is formed [log $\tau$ $\approx$ $\log$ (mass) $\approx$ 0.1].

Our calculations for the triplet give significant deviations from LTE and indicate that the observed lines are reproduced with log $\epsilon$(O) $= 8.61$ as shown in Figure 9. Allende Prieto, Lambert, & Asplund (2001b) showed that the forbidden line at 6300 Å, which forms very close to LTE conditions, is blended with a Ni i line, and considering both with a detailed three-dimensional LTE hydrodynamic model, they derived log $\epsilon$(O) $= 8.69 \pm 0.05$. Kiselman & Nordlund (1995) showed that a two-level NLTE calculation in a three-dimensional model atmosphere predicted weaker lines than the Holweger-Müller model, and we believe that differences between one dimension and three dimensions are the reason for the small remaining discrepancy. Kiselman & Nordlund (1995) find an average decrease of the total equivalent width of the triplet by about 17 mÅ when computed in three dimensions with respect to the one-dimensional value. If we change the abundance from 8.61 to 8.69 dex, the

$^8$ Here $\epsilon$(O) $= 10^{12} N(O)/N(H)$, where $N(E)$ is the number density of the element E.
calculated total equivalent width of the triplet increases by 18 mA.

A recent study of hotter (spectral types A–B) stars by Przybilla et al. (2000) has suggested that collisions with electrons as described by Van Regemorter’s formula are significantly overestimated. If such a problem applies also to solar-like stars, our abundance could also decrease, drifting away from the value derived from the forbidden line. Introducing collisions with hydrogen in the calculations might also decrease the derived abundance. The LTE profiles require an abundance of \( \log \epsilon(O) = 9.0 \) in order to fit the observed profiles.

In short, our calculations seem to bring the abundance derived from the oxygen IR triplet into agreement with that obtained by Allende Prieto et al. (2001b) from the forbidden line at 6300 Å.

3.2. Sodium

We adopt Grevesse & Sauval’s (1998) photospheric abundance, \( \log \epsilon(Na) = 6.33 \pm 0.02 \), which is indistinguishable from the meteoritic abundance \( (6.32 \pm 0.02 \) dex). Baumüller, Butler, & Gehren (1998) studied the NLTE formation of Na i lines in solar and metal-poor atmospheres and found a similar solar abundance, concluding that solar Na i profiles are best reproduced including collisions with H atoms as prescribed by Drawin (1968), but decreased by a factor of 20. From these authors’ line list, we selected several lines that appear to be clean in the solar spectrum.

Figure 10 shows our Grotrian diagram for Na i (32 levels and 192 radiative transitions) and the departure coefficients for the lowest 10 levels. The two lowest levels, which are connected by the \( D \) lines and have been identified in the

![Figure 8](image1)

**Fig. 8.** (a) Grotrian diagram for O i (see Paper I). (b) Departure coefficients for the lowest six levels of O i.

![Figure 9](image2)

**Fig. 9.** Comparison between the observed (circles) and calculated line profiles for the O i infrared triplet. The solid line shows the NLTE calculation, and the dashed line shows the LTE profiles.

![Figure 10](image3)

**Fig. 10.** (a) Grotrian diagram for Na i (see Paper I). (b) Departure coefficients for the lowest 10 levels.
figure with thick lines, are overpopulated in the photosphere compared to LTE. Most other levels are underpopulated. Our results are similar to those previously reported in the literature (see Bruls, Rutten, & Shchukina 1992 for an extended discussion). It is evident from Figure 11 that NLTE improves significantly the agreement with observations. Our tests also show, as expected based on $x^2$, that the NLTE calculations for Nai do not depend much on the near-UV opacity.

The Na $D$ lines deserve some extra comments. The core of these lines is formed in very high atmospheric layers, and therefore our results for these lines should be taken with caution. In spite of this problem, the overall agreement between our calculations and the observed $D$ lines is satisfying.

4. CONCLUSIONS AND FUTURE WORK

We have built a collection of model atoms for use in NLTE calculations for late-type stellar atmospheres. The models were compiled in an attempt to use a series of data sources as homogeneous as possible. The details are presented in Paper I. The data are formatted for the code TLUSTY (Hubeny 1988; Hubeny & Lanz 1995).

In this paper, we test the data by computing the flux emerging from the solar surface and comparing it with high-accuracy observations from space. Our calculations are based on a fixed atmospheric structure calculated in LTE, and the level populations are computed both in LTE and in NLTE. The agreement with the observed fluxes is relatively good, especially at wavelengths longer than about 2700 Å, where the LTE computed fluxes tend to be just slightly below the observations. In the region between 2400 and 2600 Å, where the Mgi bound-free opacity dominates over other sources, we find indication that the calculated LTE fluxes are larger than observed. The disagreement is even slightly enhanced for the NLTE calculations. We note that a possible opacity deficit in this window may have an impact on determinations of boron abundances from the Bi line at 2497 Å. The NLTE flux is systematically too high between 1700 and 2100 Å, where Ali photoionization plays a major role and the LTE predictions match reasonably well the observations.

The good agreement we find between observed and predicted absolute fluxes apparently contradicts a previous result by Bell et al. (2001). With the data available to us, it is not possible to clearly identify a single reason for the discrepant results. Differences between the photoionization cross sections for Mgi, Cai, Sii, and Ci, but mainly Fei, are expected. The computer codes used in the calculation are not the same; e.g., H and H$^+$ bound-free and free-free opacities may differ slightly. The model atmospheres discussed may also be somewhat different. The only obvious factor that we can suggest to be responsible for at least part of the differences is the choice of abundances. Bell et al. adopted log $\epsilon$(Mg) = 7.44 and log $\epsilon$(Fe) = 7.55. We
adopted, following Grevesse & Sauval (1998), \( \log \epsilon(\text{Mg}) = 7.58 \) and \( \log \epsilon(\text{Fe}) = 7.50 \). Grevesse & Sauval quote an uncertainty of 0.05 dex for these photospheric abundances. Their figures are also in perfect agreement with their meteoric values—these only uncertain by 0.01 dex. We approximately estimate the effect of lowering the Mg abundance on the predicted flux as an increase of 14\%, 7\%, and 3\% at 2450, 2800, and 3000 Å, respectively.

LTE and NLTE calculated fluxes systematically depart from observations below \( \sim 1700 \) Å, where Si i bound-free absorption becomes very important. We expect the formation region for these fluxes to be at very high atmospheric layers, where many of the assumptions involved in our calculations, in particular radiative equilibrium, may break down. A model with a temperature minimum (e.g., Vernazza et al. 1976) will surely perform much better in this spectral band.

From the comparison between observed and calculated fluxes between 2600 and 4000 Å, we conclude that there is no solid foundation for previous claims of missing continuum opacity in the near-UV. It has also become apparent that departures from LTE will affect the shortest wavelengths, below \( \sim 2600 \) Å. Coupling between the populations of different species that produce significant absorption in the UV is very likely, and detailed and simultaneous calculations for all of them are necessary.

Our NLTE predictions for the species that play an important role in the UV, such as Al i or Mg i, fail to match the observed optical and near-IR line profiles. In contrast, the NLTE profiles for Na i and O i, which do not absorb significantly in the UV, represent a clear improvement over their LTE counterparts. Since our NLTE computations involve adopting a fixed LTE atmospheric structure (electron pressure and temperature and gas pressure), it seems a likely possibility that the adopted structure does not represent well the physical conditions in the highest atmospheric layers, and, in turn, the level populations predicted in NLTE for UV-relevant species are wrong. However, we should exercise caution, since previous studies have successfully performed NLTE analysis of optical lines of neutral Al and Mg (Baumüller & Gehren 1996; Zhao, Butler, & Gehren 1998). Replacing our statistical approach to account for the line absorption, which is based on the concept of superlevels and opacity distribution functions, has been shown to introduce only mild differences for early-type stars (Lanz & Hubeny 2001) but may be crucial for solar-type stars. Consistent NLTE calculations to solve both the atmospheric structure and the populations must be carried out to avoid possible systematic errors in the solution of the statistical equilibrium for species such as Al i or Mg i.

An acceptable NLTE solution should reproduce satisfactorily the UV fluxes and line profiles in the UV, optical, and near-IR domains, but it is unclear that such a goal is possible within the framework of plane-parallel, homogeneous, static model atmospheres. Anderson (1989) computed a line-blanketed NLTE model in hydrostatic and radiative equilibrium for the Sun, noting significant differences in the atmospheric structure with respect to LTE for \( \tau \lesssim 10^{-3} \). Recently, Haushildt, Allard, & Baron (1999) computed consistent NLTE model atmospheres for the Sun and Vega \( (T_{\text{eff}} \sim 10,000 \text{ K}) \), finding small differences between LTE and NLTE structures for the former but important differences for the latter. However, their calculations treated both Al i and Mg i in LTE.

Our statistical equilibrium calculations neglect collisions with hydrogen atoms. Such omission does not prevent us from obtaining a good match of the observed line profiles of O i and Na i lines, but it might have a more important effect on Mg i and Al i (see, e.g., Baumüller & Gehren 1996; Zhao et al. 1998). Although our success in matching within a few percent the solar absolute flux between 2700 and 4000 Å is encouraging, validation of the atomic models presented in Paper I requires further investigation, considering a self-consistent NLTE calculation of the atmospheric structure and the effect of H collisions. Our LTE tests have shown CO to not be very important in accurately modeling the solar UV flux, but this and other molecular species, in particular OH and CH (see Kurucz, van Dishoeck, & Tarafdar 1987) should be properly considered in NLTE to secure this result. Finally, enlarging the set of available high-accuracy UV spectrophotometry by observing other nearby stars is necessary, as it is to explore the effect of granulation on the UV flux.

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