NON-LTE MODEL ATMOSPHERES FOR LATE-TYPE STARS I. A COLLECTION OF ATOMIC DATA FOR LIGHT NEUTRAL AND SINGLEY-IONIZED ATOMS.

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ABSTRACT

With the goal of producing a reliable set of model atoms and singly-ionized ions for use in building NLTE model atmospheres, we have combined measured energy levels, critically-compiled line transition probabilities, and resonance-averaged calculations of photoionization cross-sections. A majority of the elements from Li to Ca are considered, covering most of the important species in late-type atmospheres. These include elements which contribute free electrons and/or continuous opacity in the ultraviolet (e.g., Mg, and Si), as well as trace elements whose abundance determinations rely on ultraviolet lines (e.g., B from B I lines). The new data complement and, for the species in common, supersede a previous collection of model atoms originally designed for use in studies of early-type stars.

Subject headings: Atomic data — radiative transfer — stars: atmospheres

1. INTRODUCTION

Classical – Local Thermodynamical Equilibrium (LTE), plane-parallel, horizontally homogeneous, hydrostatic equilibrium – model stellar atmospheres have been providing a basic tool for stellar spectroscopy for several decades, but are now known to suffer from various weaknesses when applied to accurate observations of individual stars. Several lines of research have been adopted to improve the models. For example, in the context of late-type stars, we mention here three-dimensional hydrodynamical simulations of surface convection (e.g. Stein & Nordlund 1998, Asplund et al. 2000); improvements in molecular opacities (e.g. Hauschildt et al. 1999a; Tsuji 2002); the adoption of spherical geometry (e.g. Plez, Brett, & Nordlund 1992; Hauschildt et al. 1999b); and semi-empirical modeling (e.g. Allende Prieto et al. 2000).

LTE has been one of the strongest hypotheses invoked extensively in solving the coupled problems of radiative transfer and structure in stellar atmospheres. This assumption enormously simplifies the complexity of the calculations, since the populations of all ions and molecules involved follow from the Boltzmann and Saha formulae. Yet, LTE has been recognized to be inappropriate in many areas of the Hertzsprung-Russell diagram. Models that take departures from LTE into account are traditionally labeled non-LTE (or NLTE) models. The main area where the NLTE models have been applied are hot stars (types O, B, A, hot white dwarfs and subdwarfs, and other objects with high-temperature atmospheres; see, e.g., Hubeny & Lanz 1995). However, the advent of large telescopes with high-dispersion spectrographs, and the subsequent refinement of observations of late-type stars, call for an assessment of the possible departures from LTE on the model atmospheres for these stars.

Non-LTE calculations require detailed radiative and collisional rates of all involved transitions in order to solve the statistical equilibrium equations. The role of photoionization cross-sections should be emphasized, because changes of the degree of ionization (with respect to the LTE ionization equilibrium) are a major non-LTE effect in stellar atmospheres. Not all of the required energies and cross-sections for the atomic/molecular processes that play a role in a stellar atmosphere are available. Nonetheless, the available data has been expanded in recent years. Large collaborative projects, such as the Opacity Project (see, e.g., Cunto et al. 1993), the Iron Project (see, e.g. Butler 1998), and SAM (see, e.g. Brage, Judge, & Brekke 1996) have been enormously helpful. Long-term efforts on compilation of data, such as CHIANTI (e.g., Dere et al. 1997), VALD (Kupka et al. 1999), and the Atomic Spectroscopic Database (ASD) at the National Institute of Standards and Technology (NIST), supplemented by numerous contributions from individuals and small groups, are to be noted.

The model atoms presented here are built for use in the model stellar atmosphere code TLUSTY (Hubeny 1988, Hubeny & Lanz 1995). A family of model atoms and ions, primarily in the context of hot stellar atmospheres, has been made publicly available with the code\(^1\). These models are briefly described in §2. Section 3 is devoted to the new set of model atoms, describing the numerical details of the smoothing process applied to the photoionization cross-sections, and the construction of model atoms. Some comments on the limitations and practicalities for using these data, as well as a summary, are outlined in §4.

2. THE MODION MODEL ATOMS

In the context of hot stellar atmospheres, a collection of model atoms for H I, He I, He II, C I–C IV, N I–N V,
O II–O VI, Ne II–Ne IV, Mg I–Mg II, Si I–Si IV, and S II–S VI was prepared, ranging from very simple to quite complete structures. These models are essentially based on data extracted from TOPBASE. To manipulate these large sets of atomic data, an interactive, IDL-based tool, was developed: MODION (Varosi et al. 1995; see also Lanz et al. 1996). This interface program works with three files for each ion, containing the level energies, the line oscillator strengths, and the photoionization cross-sections, as extracted from TOPBASE. The energy files have been updated with observed energies extracted from ASD/NIST (Martin 1997; Wiese 1997), so that all transitions will be calculated at their actual frequency.

MODION allows model atoms of various sophistication to be built by displaying a Grotrian diagram from which the explicit NLTE levels are interactively selected. Although it might seem desirable to include as many levels as possible, this is often impracticable due to computing time and memory limitations. To overcome these limitations, some individual levels are merged into superlevels (see Hubeny & Lanz 1995). Low-excitation levels are generally considered as individual levels, while levels of higher excitation are merged. The most excited levels are often not treated explicitly, but are assumed to be in LTE with respect to the ground state of the next ion. Model atoms and ions have been built for different purposes: simple model atoms (typically less than 15 explicit levels) are often quite appropriate for inclusion in photospheric structure calculations, while very detailed models (over 40 explicit levels) may be required for detailed line formation studies.

After the level selection step, MODION builds a list of bound-bound and bound-free transitions. Oscillator strengths from TOPBASE are assigned to bound-bound transitions between individual levels. MODION takes care of the appropriate summing and averaging for transitions between superlevels, supplementing TOPBASE data with hydrogenic values when data are missing. The necessary sums are similarly performed for photoionization cross-sections. Tlusty is able to deal with detailed and complex representations of the cross-sections, but in most cases we use approximate, yet adequate, representations. Using MODION, we display the cross-sections in a log–log plot of the photoionization cross-section vs. frequency, and hand-pick some points with a cursor. The approximate cross-sections are selected to be the lower envelopes of the detailed cross-sections, thus the autoionization resonances are mostly neglected. Finally, when the selections have been completed, MODION writes out a data file in the format required by Tlusty. Some limited upgrades have been made in a later stage to incorporate Stark profiles for strong resonance lines or to introduce fine-structure in strong resonance doublets like C IV λ1550 or Si IV λ1496.

3. THE RAP MODEL ATOMS

This new set of model atoms is, like the MODION models, based on data from TOPBASE and NIST. They treat, however, the photoionization cross-sections differently, and in more detail. As they are new and have never been used in calculations of radiative transfer and model atmospheres before, we describe them in depth. These models are, at the time of this writing, available for neutral Na and S, singly ionized Ne, and neutral and singly-ionized Li, Be, B, C, N, O, F, Mg, Al, Si and Ca.

3.1. Resonance-Averaged Photoionization Cross-Sections

It has been acknowledged that errors in the computed energies of the atomic levels may result in spurious shifts of the frequencies at which strong photoionization resonances are predicted by theoretical calculations. Consequently, several authors have suggested different procedures to smooth the Opacity Project data (see, e.g., Verner et al. 1996; Bautista, Romano, & Pradhan 1998). In addition, smoothing the cross-sections reduces sometimes the number of data points to a more manageable level.

Bautista et al. (1998) suggest a recipe for a convenient Gaussian smoothing. They recommend a value for the width of the Gaussian of $\sigma = 0.03E$, where $E$ is the energy of the ionizing photon. They apply such a smoothing to the photoionization cross-sections of ground levels of all atoms and ions included in TOPBASE and to new data on Fe I–Fe V provided by the Iron Project, producing Resonance-Averaged Photoionization (RAP) cross-sections. While in low-density environments, such as gaseous nebulae, virtually all atoms and ions are in ground states, this is not the case for stellar atmospheres. Extending the calculations of RAP cross-sections to the rest of the levels is therefore desirable. We deal with neutral and singly-ionized species of the elements included in TOPBASE that have been described by LS coupling in ASD/NIST, excluding H and Fe. In fact, the list covers most of the atomic species of relevance for studying late-type stellar atmospheres.

We have closely followed the procedure described by Bautista et al. (1998). The RAP cross-section at a given energy, $\sigma_A(E)$, is computed from the TOPBASE photoionization cross-section, $\sigma(E)$, through the integral

$$\sigma_A(E) = \frac{\int_{E_0}^{\infty} \sigma(x) \exp \left[-\frac{(x - E)^2}{2(\delta E)^2}\right] dx}{\int_{E_0}^{\infty} \exp \left[-\frac{(x - E)^2}{2(\delta E)^2}\right] dx}$$

(1)

where $E_0$ is the ionization threshold energy, and $\delta E = 0.03E$. $E_0$ is slightly lower than the energy difference between the level and the continuum, due to line merging near the series limit.

To speed up the calculations, without losing accuracy, we restricted the limits of the integral (1) to $E \pm 5\delta E$. In order to avoid unwanted systematic effects at the minimum (threshold) and maximum energies in the TOPBASE calculations, we performed a linear interpolation over the energies for which less than five points were available within $\pm 5\delta E$. The RAP cross-sections were derived at energies separated by the smallest steps allowed by the sampling theorem, using the recurrence formula $E(i + 1) = E(i)(1 + 5\delta E/E)$ from $E = E_0$ to $E \leq E_{MAX}$. Figure 1 shows two examples corresponding to the ground levels of Na I, and Ca I: the thin solid line corresponds to the original cross-sections, and the filled dots represent the RAP cross-sections.

3.2. Assembling the RAP Model Atoms

The following sections describe how radiative and collisional processes are accounted for in the the RAP model
Fig. 1.— Detailed (solid line) and resonance-averaged (filled circles) cross-section for the ground states of Na I and Ca I. These two cases exemplify a smooth cross-section and a complex resonance structure.

atoms. Only collisions with electrons are included. Collisions with neutral H atoms may be important in late-type stars, but lacking term-dependent or species-dependent data, they are not considered in these models. The phenomenological approximations usually found in the literature are best implemented directly in the NLTE codes, rather than in the input data files.

3.2.1. Radiative processes

The Opacity Project provides energies and oscillator strengths for atomic levels and radiative transitions among them. However, even though this database provides a large amount of atomic data of sufficient quality for many purposes, theoretical calculations cannot, with few exceptions, predict the energies of the levels with accuracy. As a result, the wavelengths of the lines cannot be predicted to the precision available to laboratory spectroscopists. There are also measurements of transition probabilities that may be more accurate than those in the OP database.

We have chosen to use the atomic energy levels and the spectral lines included in ASD/NIST, version 2.0, to build models for the same atoms and singly-ionized ions for which the have derived RAP cross-sections from TOPBASE data. The photoionization cross-sections are given as a function of the energy from the threshold, and therefore they are simply shifted to the observed energy levels. TOPBASE ignores fine structure, and so have we, by grouping the split levels into a single one with an averaged energy, using \((2J + 1)\) as weights (where \(J\) is the quantum number that represents the total angular momentum), according to the relative populations of the levels expected in thermodynamic equilibrium. Transitions between fine-structure states of a given level are ignored.

A scaled hydrogenic photoionization cross-section has been assigned to the levels whose photoionization cross-sections were not listed in TOPBASE, assuming that the ionization takes place to the ground state of the next ion:

\[
\sigma(\nu) = 2.815 \times 10^{29} \frac{(Z + 1)^4}{\nu^4 n^3} \frac{g_{II}}{(Z + 1)^2} \frac{n}{\nu} \text{ cm}^2
\]

\((\nu \geq \nu_0 \equiv E_0/h)\),

where \(h\) is Planck’s constant, \(n\) is the quantum principal number of the last electron in the configuration, \(\nu\) the frequency, \(Z\) the charge of the ion (i.e., \(Z = 0\) for neutrals, \(Z = 1\) for once ionized, etc.), and \(g_{II}\) the Gaunt factor expressed as

\[
g_{II}(n, \nu) = \sum_{i=1}^{7} C_i^n \nu^{i-4}
\]

with the coefficients \(C_i^n\) given by Mihalas, Heasley, & Auer (1975). C.g.s. units are used throughout the paper.

The radiative transitions between fine-structure states \((i, j)\) of two levels \((l\) and \(u\)) have been summed to a single one with a \(gf\)-value:

\[
g_l f_{lu} = \sum_i g_i \sum_j f_{ij}
\]

where \(g_i = 2J + 1\) represents the statistical weight of a fine structure level.

Allowed and forbidden radiative transitions whose \(f\)-values are listed in the NIST database have been included in the models. Also, allowed radiative transitions not listed in NIST have been included, assuming a scaled hydrogenic transition probability

\[
f_{ij} = f_{ij}^H \frac{g_i}{2n_i^2}.
\]

When more than one level in TOPBASE – with separate photoionization cross-sections – was listed with identical energies in the NIST lists, they were included in the models with their respective RAP cross-sections. The states described in the NIST database with a coupling other than \(LS\) have not been included, but states with configurations, terms, or energies listed as uncertain are included when

\(^4\)We note that, in some particular cases, NIST may list theoretical calculations less accurate than OP.
matched by the TOPBASE states within 0.08 Ryd. Only levels with energies lower than the series limit are kept. As an example, Figure 2 displays the Grotrian diagrams for Na I and Si I. Table 1 lists the number of levels and radiative transitions considered for each model.

We have formatted the described data to be read by the program TLUSTY. The code is designed to build non-LTE model atmospheres, and it will be the tool we shall employ in future analyses of stellar spectra. There are several documents explaining the data format in detail (Hubeny 1988; Hubeny & Lanz 1997), hence we shall not describe it here.

## 3.2.2. Collisional processes involving electrons

The collisional rate for the transition \( i \rightarrow j \) is given by \( n_e q_{ij} \), where \( n_e \) is the number density of electrons and \( q_{ij} \) is the excitation rate coefficient. Excitations induced by electron collisions between states connected by radiatively permitted transitions are accounted for using Van Regemorter’s formula (Van Regemorter 1962, Mihalas 1972), with the excitation rate coefficient as:

\[
q_{ij} = \pi a_0^2 \sqrt{\frac{8k}{m_e \pi}} \frac{8\pi}{\sqrt{3}} \sqrt{T} f_{ij} \left( \frac{I_H}{E_{ij}} \right)^2 U_0 e^{-U_0 \Gamma(U_0)} \
\approx 19.7 \frac{f_{ij}}{T^{3/2} U_0} e^{-U_0 \Gamma(U_0)} \text{ cm}^3\text{s}^{-1},
\]

(6)

where \( a_0 \) is the Bohr radius, \( k \) is Boltzmann’s constant, \( m_e \) is the mass of the electron, \( I_H \) is the threshold ionization energy for hydrogen, \( T \) is the electron temperature, \( U_0 = E_{ij}/kT \), and for ions

\[
\Gamma(U_0) = \max \left[ \frac{\sqrt{3}}{2\pi} e^{U_0 E_1(U_0)} \right]
\]

(7)

with \( \gamma = 0.7 \) (transitions between levels with the same principal quantum number) or \( \gamma = 0.2 \) (otherwise) (Mihalas 1978), \( E_1 \) is the first-order exponential integral, but for neutral atoms

\[
\Gamma(U_0) = \frac{0.066}{U_0} \left( 1 + \frac{3}{U_0} \right), \quad U_0 > 14
\]

(8)

(Auer & Mihalas 1973). Collisional excitation between levels linked by forbidden radiative transitions is considered by means of the Eissner-Seaton formula (Seaton 1962):

\[
q_{ij} = \frac{8.631 \times 10^{-6}}{g_i \sqrt{T}} e^{-U_0 \gamma_{ij}} \text{ cm}^3\text{s}^{-1},
\]

(9)

adopting \( \gamma_{ij} = 0.05 \) for all cases. Pradhan & Peng (1995) and Pradhan & Zhang (2000) review some of the detailed calculations and scaling laws of effective collisional strengths that are available for particular ions. Those data should update the approximate values adopted here.

We also used an approximate formula (Seaton 1962) to evaluate collisional ionizations:

\[
q_{ij} = \frac{1.55 \times 10^{13}}{U_0 \sqrt{T}} e^{-U_0 \sigma_0} \text{ cm}^3\text{s}^{-1},
\]

(10)

with the photo-ionization cross-section at the threshold \( \sigma_0 \) from TOPBASE cross-sections (when available), or the hydrogenic approximation (with the Gaunt factor equal to one)

\[
\sigma_0 = 7.91 \times 10^{-18} \left( \frac{n}{Z+1} \right)^2 \text{ cm}^2
\]

(11)
Fig. 3.— Relative difference between the bound-free continuum flux from H and H$^-$, and the same plus the contribution from C, N, O, Mg, Al, or Si, for Kurucz’s model atmospheres with the stellar parameters of the Sun (G2V) and Procyon (F2 IV-V).

where $n$ is again the principal quantum number of the last electron and $Z$ the charge of the ion. Collisional recombinations and de-excitations follow from the principle of detailed balance. Detailed calculations should replace these approximate values where available (see, e.g., Nahar & Pradhan 1997 and Nahar 1999).

4. SUMMARY

We have smoothed the photoionization cross-sections of the Opacity Project for neutral Na and S, singly ionized Ne, and neutral and singly-ionized Li, Be, B, C, N, O, F, Mg, Al, Si and Ca, using a Gaussian profile with $\sigma = \delta E = 0.03E$, where $E$ is the energy of the ionizing photon. This procedure follows Bautista et al. (1998). The smoothed cross-sections have been merged with the energy levels and line transition probabilities listed in the Atomic and Spectroscopic Database at NIST to derive model atmospheres and line formation. This new collection of model atoms complements and, for the species in common, supersedes a previous dataset, the MODION model atoms, developed for early-type stellar atmospheres.

As an example, we show the results of two calculations involving the RAP models. Figure 3 shows the relative importance of neutral C, N, O, and Mg on the continuum absorption in the near-UV spectrum of the Sun ($T_{\text{eff}} = 5777$ K; log $g = 4.44$ dex; [Fe/H]=0.0 dex) and Procyon ($T_{\text{eff}} = 6530$ K; log $g = 4.0$ dex; [Fe/H]=0.0 dex). The spectral synthesis assumes LTE and makes use of Kurucz’s atmospheric structures (Kurucz 1993).

Although the models are based on observed energy levels and lines, together with detailed calculations of photoionization cross-sections, judging their appropriateness for non-LTE calculations in stellar atmospheres is beyond the scope of this paper. Several approximations and simplifications are implicit in the models and, therefore, caution is required. Only detailed comparison with high quality observed spectra will determine the models’ usefulness. More complex ions not yet included in TOPBASE are of interest. Iron is at the head of this group, and new calculations of photoionization cross-sections are available (Bautista 1997) – but not as part of TOPBASE at the time of this writing. Many other sources of data, although with a significant heterogeneity, exist and should be used to complement, check, and improve these models. Such tasks and a detailed comparison with high-quality observations for a series of standard stars are in progress and will be reported in the future.

Both, the MODION models$^5$ and the RAP models$^6$ (and, independently, the RAP photoionization cross-sections) are publicly available.

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REFERENCES

Allende Prieto, C., García López, R. J., Lambert, D. L. & Ruiz Cobo, B. 2000, ApJ, 528, 885
Asplund, M., Nordlund, A., Trampedach, R., Allende Prieto, C., & Stein, R. F. 2000a, A&A, 359, 729.
Auer, L H. & Mihalas, D. 1973, ApJ, 184, 151
Bautista, M. A. 1997, A&AS, 122, 167
Bautista, M. A., Romano, P. & Pradhan, A. K. 1998, ApJS, 118, 259
Brage, T., Judge, P. G. & Brekke, P. 1996, ApJ, 464, 1030
Butler, K. 1998, Atomic and Molecular Data and their Applications, AIP Conference Proceedings, Peter J. Mohr and Wolfgang L. Wiese, eds., vol. 434, 1998., p 23
Cunto, W., Mendoza, C., Ochsenbein, F. & Zeippen, C. J. 1993, A&A, 275, L5
Dere, K. P., Landi, E., Mason, H. E., Monsignori Fossi, B. C. & Young, P. R. 1997, A&A, 125, 149
Haussdörf, P. H., Allard, F. & Baron, E. 1999a, ApJ, 512, 377
Haussdörf, P. H., Allard, F., Ferguson, J., Baron, E. & Alexander, D. R. 1999b, ApJ, 525, 871
Hubeny, I. 1988, Computer Phys. Comm., 52, 103
http://tlusty.gsfc.nasa.gov
http://hebe.as.utexas.edu/at/at.cgi
Hubeny, I. & Lanz, T. 1995, ApJ, 439, 875
Hubeny, I. & Lanz, T., 1997, TLUSTY User’s Guide, Version 195
(http://tlusty.gsfc.nasa.gov/)
Kupka, F., Piskunov, N., Ryabchikova, T. A., Stempels, H. C. & Weiss, W. W. 1999, 
A&AS, 138, 119
Kurucz, R. 1993, ATLAS9 Stellar Atmosphere Programs and 2 km/s 
grid. Kurucz CD-ROM No. 13. (Cambridge, Mass.: Smithsonian 
Astrophysical Observatory).
Lanz, T., Hubeny, I. & de Koter, A. 1996, Phys. Scr., T65, 144
Martin, W. C., 1997, Working Group 1 Report for the 
IAU, Commission on Atomic and Molecular data 
(http://physics.nist.gov/PhysRefData/datarefs/contents.html)
Mihalas, D. 1972, ApJ, 177, 115
Mihalas, D. 1978, Stellar Atmospheres, 2nd Edition, (San Francisco: Freeman), p. 133
Mihalas, D., Heasley, J. N., & Auer, L. H. 1975, NCAR Technical 
Note NCAR-TN/STR-104
Nahar, S. N. 1999, ApJS, 120, 131
Nahar, S. N.,& Pradhan, A. K. 1997, ApJS, 111, 339
Plez, B., Brett, J. M., & Nordlund, Å. 1992, A&A, 256, 551
Pradhan, A. K. & Peng, J. 1995, in Analysis of Emission Lines, R. 
E. Williams and M. Livio, eds., STScI Symposium Series No. 8, 
(Cambridge: Cambridge University Press)
Pradhan, A. K. & Zhang, H. L. 2000, Landolt-Börnstein: Numerical 
Data and Functional Relationships in Science and Technology, Y. 
Itikawa, ed., (Berlin: Springer), in press
Seaton, M. J. 1962, in Atomic and Molecular Processes, ed. D. R. 
Bates (New York: Academic Press), p. 374
Stein, R. F. & Nordlund, Å. 1998, ApJ, 499, 914
Tsui, T. 2002, ApJ, 575, 264
Van Regemorter, H. 1962, ApJ, 136, 906
Varosi, F., Lanz, T., deKoter, A., Hubeny, I. & Heap S.R. 1995, 
ftp://idlastro.gsfc.nasa.gov/pub/contrib/varosi/modion
Verner, D. A., Ferland, G. J., Korista, K. T. & Yakovlev, D. G. 1996, 
ApJ, 465, 487
Wiese, W. L., 1997, Working Group 2 Report for the 
IAU, Commission on Atomic and Molecular data 
(http://physics.nist.gov/PhysRefData/datarefs/contents.html)
Table 1
Number of Levels and Radiative Transitions Included in the Different Models.

| Model | Num. Levels | Num. Transitions | Model | Num. Levels | Num. Transitions |
|-------|-------------|------------------|-------|-------------|------------------|
| Li I  | 26          | 153              | Li II | 37          | 143              |
| Be I  | 56          | 323              | Be II | 18          | 72               |
| B I   | 29          | 117              | B II  | 38          | 134              |
| C I   | 104         | 1090             | C II  | 40          | 189              |
| N I   | 89          | 615              | N II  | 51          | 280              |
| O I   | 54          | 242              | O II  | 74          | 512              |
| F I   | 52          | 209              | F II  | 73          | 326              |
| ...   | ...         | ...              | ...   | ...         | ...              |
| Ne I  | 59          | 353              |       |             |                  |
| Mg I  | 71          | 434              | Mg II | 31          | 184              |
| Al I  | 33          | 160              | Al II | 81          | 537              |
| Si I  | 57          | 215              | Si II | 46          | 261              |
| S I   | 64          | 313              |       | ...         |                  |
| Ca I  | 79          | 543              | Ca II | 32          | 147              |
$F \, (\text{erg cm}^{-2} \, \text{s}^{-1} \, \text{A}^{-1})$