ELSA: A semi-automated, nebular abundance package

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ABSTRACT

We describe ELSA, a package for analyzing emission lines to derive nebular diagnostics and chemical composition for photoionized nebulae. In addition to allowing easy input of fluxes from line-measuring programs and providing output of nearly publication-ready LaTeX tables, ELSA incorporates rigorous calculation of the Balmer decrement, ionized helium Balmer contamination, reddening parameter c, and uncertainty propagation. ELSA's modular design makes it easy to update, customize and maintain. Source code, binaries, and documentation are available for download.

Subject headings: Data Analysis and Techniques, ISM

1. Introduction

ELSA (**E**mission **L**ine **S**pectrum **A**nalyzer) is a software package for the analysis and management of spectroscopic emission line data from photoionized nebulae. It has the dual goals of providing a flexible, extensible, updateable code and automating many of the tedious, repetitive tasks of data analysis.

Deriving characteristics such as chemical abundances, temperatures and densities for photoionized nebulae is often a lengthy, multi-step process. The original motivation behind the development of ELSA was to combine many of the steps commonly used in the pipeline for obtaining these quantities into a more streamlined, consistent operation; the secondary goal was to reduce the amount of manual transfer and reformatting of data to minimize time, labor, and the opportunity for human error. To this end, ELSA provides tools to integrate many of the steps involved in these pipelines.

ELSA is written in C, which provides for a high level of portability and versatility. Downloads are available at http://www.williams.edu/Astronomy/research/PN/elsa/. We provide pre-compiled binaries for Mac OS X, Solaris and Linux; compiling from source code should be possible for any platform for which a C compiler is easily available. Once compiled, the ELSA program provides an interface to multiple tasks for managing and analyzing data. A list of tasks and full documentation for each task are available on the ELSA website and in the distribution package itself. Also of note is the configuration file: this is a text file containing a series of parameters defining how ELSA will operate, and it is intended to be edited easily by the user. For example, many of the tasks in ELSA are toggled so that the user can decide whether or not to apply a particular step or carry out a particular calculation. The documentation also contains input and output files for a test nebula so that users can check that their installation of ELSA was successful. **Matt - check IC5217's results from the locked version of ELSA and make sure it agrees**

with what's in the paper's tables.

An overview of ELSA's capabilities is given in §2, while §3 describes a typical run. In §4 we explain tasks, options and input/output; in §5 we detail the calculations ELSA can perform; in §6 we point out the limitations to what is included in the calculations and also describe our testing of ELSA; and in §7 we describe how to update atomic constants.

2. Overview of ELSA

We outline here the steps required to go from a raw line-flux file through the analysis to formatted output. The general flow of tasks in ELSA begins with data input. Data consists of one or more text files of emission-line fluxes with wavelengths that can range from the ultraviolet to the infrared. After some bookkeeping tasks that organize the file(s) into the proper format, processing can begin. ELSA will calculate the Balmer decrement appropriate to the object's temperature and density to yield a value for c, the reddening at Hβ, and at the same time, correct for contamination of the Balmer lines by coincident lines of ionized helium. This correction loop will be described in more detail in §5.1. Once the corrected line strengths have been derived, ELSA performs the plasma diagnostics, which provide temperatures and densities from standard forbidden-line ratios, along with ionic abundances. Total abundances are also reported; these are calculated using ionization correction factors described in §5.4. The user can opt to have the calculated uncertainties included in the output, which can be specified as plain text or LaTeX formatted tables of observed and corrected line intensities, plasma diagnostics, and tables of ionic and total abundances.

3. An Example Run

What follows is a walk-through of a standard run of ELSA from start to finish, with brief descriptions of tasks and options that will be explained in more detail in subsequent sections. The tasks come in a logical order, following the steps one would take to manually process the data. As raw input we will use splot logs for the planetary nebula IC 5217 from **?**, observed at the 2.1-m telescope with the Goldcam spectrograph at Kitt Peak National Observatory in June 1999. Red and blue grating settings cover the range $\lambda\lambda$3650-6750 and $\lambda\lambda$5700-9600, respectively, with files named 5217blue.txt and 5217red.txt, both of which are included in their entirety in Appendix A. Below is a portion of 5217blue.txt. The first and third columns are the only relevant ones; the second column is the continuum level, which, along with any line-fitting results from the last four columns, is ignored by ELSA.

File: 5217blue.txt

Mar 28 13:56 [IC5217]: IC 5217

center	cont	flux	eqw	core	gfwhm	lfwhm
3726.176	1.874E-14	9.807E-13	-52.91			
3751.799	1.633E-14	1.344E-13	-8.218			
3769.85	1.534E-14	1.351E-13	-8.772			
3797.089	1.171E-14	2.417E-13	-20.69			
3834.22	9.214E-15	3.374E-13	-36.64			
3867.354	8.989E-15	5.189E-12	-577.2	6.687E-13	7.289	0.
3887.247	6.592E-15	9.736E-13	-147.7	1.255E-13	7.289	0.

3.1. Unduplicating Multiple Measurements of a Line

Occasionally when measuring a spectrum, one might measure a line twice to check the effect of changing the continuum level or to compare results from manual and line-fit measurements. The resulting logfile will therefore contain multiple flux values for the same line. In ELSA, the first thing to do for each logfile is to choose which of multiple measurements for a single line will be used in the succeeding analysis. In our example, only the blue file has a multiple measurement. We run the splot_undup command:

```
$ elsa splot_undup 5217blue.txt u5217blue.txt
```

which produces the following screen output:

```
Unduping IRAF log file '5217blue.txt'...
Reading data from input files...
Finding duplicates...
Overlap found. Please select which line to use.
(1) 5514.726000 2.482000e-14
(2) 5514.825000 2.391000e-14
Use which line? [1-2]:
```

We choose to use the first of the two measurements, and type a 1, after which the task completes. Our new logfile is u5217blue.txt.

3.2. Merging Multiple Wavelength Files

If the observations span two grating settings, or even two different wavelength regimes, they will have to be merged somehow. Also, if the two input logfiles overlap in wavelength, the user will need to choose which measurement to use,

in a similar manner as splot_undup. The splot_merge task addresses these issues:

```
$ elsa splot_merge u5217blue.txt 5217red.txt 1.0 5217.txt
```

where the two logfiles are listed, followed by the scale factor required to multiply the second file's fluxes to match the first, and the name of the resulting merged file. The user is shown the flux values of any line present in both files, and asked to choose one, e.g.:

```
Merging IRAF log files 'u5217blue.txt' and '5217red.txt'...
Reading data from input files...
Finding overlaps...
Overlap found. Please select which line to use.
(1) In u5217blue.txt: 5751.56 5.988e-15 5.142e-14
(2) In 5217red.txt: 5753.33 6.428e-15 4.134e-14
Use which line? [1-2]:
```

We choose 1 in this case, and continue until all multiple measurements have been dealt with. The merged file 5217.txt is now ready for further processing.

3.3. Flagging Unidentified Wavelengths and Long Comments

The next step is to see if there are any unidentified lines or extra-long comments from the original logfile(s) that will not fit in the final line intensity table. We run splot_flag, which requires the object's radial velocity (-98.6 km/s; **?**) so that observed wavelengths can be appropriately matched to rest wavelengths in ELSA's master wavelength table:

```
$ elsa splot_flag 5217.txt -98.6 flag.txt
```

where flag.txt is the file we have created to store the results. When we examine flag.txt we

see:

Long Comments

9541.591 3.750e-13 all lines like Pa and CI and Ar IV are weak

Unknown Wavelengths

3751.799 1.344e-13

The long comment is reproduced from the original logfile for our information, but we want to remove it from the file; otherwise it will create a line in the final output that runs off the page. The single unidentified line is H12, a high Balmer line not included in the master list and not used for any calculation, so we ignore it and it will not be processed further.

3.4. Creating a Formatted Table of Line Intensities

We are now ready to create a LaTeX formatted table that will include, among other things, the line identifications, measured fluxes *F(λ)*, and reddening-corrected line intensities, *I(λ)*. We run the splot_table task, using the -t option requesting LaTeX output, and again including the radial velocity of this object:

```
$ elsa -t splot_table 5217.txt -98.6 5217lines.tex
```

The resulting file after LaTeXprocessing, is 5217lines.pdf, which is displayed as Table 1 in Appendix B; the plain text version that results from omitting the -t is displayed as Table 2. The superscript *a* denotes lines whose intensities have been calculated mathematically ("deblended"), as described in §5.2.

3.5. Calculating Abundances

The last step is running the splot_abun task on the file 5217.txt, once again including the radial velocity:

```
$ elsa -te splot_abun 5217.txt -98.6 5217abun.tex
```

which creates LaTeX formatted tables of plasma diagnostics and abundances including calculated uncertainties as shown in Appendix C; the -t option is not strictly necessary, as this is the only output format for such a table. When there are multiple values for an ionic abundance, starred values indicate which are used in the final calculations (see documentation for details).

4. Details on Tasks, Options, Input and Output

Now that we have briefly illustrated a typical pass through ELSA, we describe tasks and options in more detail.

4.1. Task Organization

The various functions of ELSA are organized as "tasks." All tasks are available from the ELSA binary program. Each task is invoked by name from the command line as an argument to the ELSA binary; the various task names are listed and described here. Each task also requires certain arguments which vary by task. Some tasks require one or two input data files, and some tasks require a numerical scale factor or radial velocity to identify wavelengths and fluxes correctly. Typing elsa -h at the system prompt will produce a listing of available options and tasks with brief descriptions. **Matt - check that this is**

complete and correct for the locked version of ELSA.

4.2. Command Line and Configuration File Options

ELSA reads task parameters and options from the command line and from a configuration file. The command line looks generically like the following:

```
$ elsa <options> <task> <argument(s)>
```

An example of a command-line parameter is the "-e" option that controls whether full uncertainty propagation will be performed (§4.4). Options also exist to toggle the output format between LaTeX and plain text, to choose whether to read flux uncertainties from an external file or from comments in the log file itself, and whether to impose a pre-determined value of c.

The configuration file contains: the rest wavelengths of Hα, Hβ, Hγ, Hδ, He II λ4686, [O III] λ4363/λ5007 and [S II] λ6716/λ6731, all of which are used for extinction corrections or plasma diagnostics before any tabular or abundance output is created; the name of a file containing the wavelengths to be processed; the nominal ratios of the Balmer lines used for extinction corrections; the maximum number of input lines (to control memory allocation); and a series of toggles controlling (i) whether a dynamic recalculation should be made of the Balmer line ratio, (ii) whether particular pairs of unresolved lines lines should be deblended, and (iii) whether underlying stellar absorption should be taken into account (for extragalactic sources), all described in section §5.3. The default configuration file is shown in Appendix D.

4.3. The Reference Wavelength File and Line Identification

ELSA internally recognizes a large number of ions and their corresponding emission lines for which abundances can be calculated (see Table 1). However, it also offers users the option to choose a relevant subset of lines in final tabular and abundance output. The selections are made using a simple text file containing a list of the rest wavelengths of the emission lines interest to the user along with a short text description of the line's source (usually the name of the ion producing the line). The wavelength file also may contain lines, marked with an asterisk, which should be deblended in the manner described in §5.2. An excerpt from the default wavelength file is given in Appendix E.

In theory, users could include as many or as few lines as they wished in the wavelength file. However, in order for the calculations and diagnostics to work, certain lines must be present in the wavelength file. If they are not, ELSA will ignore them and assume they were not observed, which will produce erroneous results when calculations requiring those lines are attempted. For example, if [O III] λ5007 is not included in the wavelength file, all $T_{[\mathrm{OIII}]}$ calculations will fail, as will all ionic abundance calculations that rely on $T_{[\mathrm{OIII}]}$. For a full list of such dependencies, see Table 2. **Matt- you need to create Tables 1 and 2 or remove references to them.**

The name of the wavelength file is read at run time in the configuration file, elsa.conf, as the filename specified by the parameter SpecFile. Thus, it is possible to maintain numerous different wavelength files for different types of objects. Wavelengths in ELSA are always given in Angstroms. As ELSA runs, it reads the list of lines from the wavelength file, creating a pool of "reference lines." It then attempts to match each line in the input data with one of the lines in this pool. A line from the input data is considered to match a line in the reference line pool if it falls within a specified wavelength tolerance (the MaxTolerance parameter, which is also given in the configuration file). All lines in the data

files are redshift-corrected before any attempts to match are made. The default value of MaxTolerance in the optical region is 4.0 Angstroms. If you have trouble with too many lines appearing to be duplicates, or ELSA not finding lines correctly, MaxTolerance can be adjusted accordingly. However, it is important to keep in mind that ELSA was designed for moderate-resolution spectra; high-resolution spectra with typical line separations approaching the value of MaxTolerance will not be handled properly by ELSA.

4.4. Line Flux Input

Input to ELSA can be read directly from the output of the splot task in IRAF[1], as shown in Appendix A. Tabular data not specifically in this format can be appropriately converted using ELSA's convert_data task, as described below, or simply created as a new text file, as shown in Appendix F. Data for multiple objects can be entered together; a file containing a list of target file names is read, similar to the handling of the "@-file" in IRAF. The tasks described in the following subsections are available to modify and prepare splot logs for calculation with ELSA.

ELSA contains the capability to compute formal uncertainties for any output quantity (including nebular abundances, temperatures, densities and corrected line intensities). In order to do this, input must include a formal uncertainty for each line strength. There are two means of providing this input. ELSA can read flux uncertainties from comments in an splot log file. A comment containing one colon character is assumed to have an uncertainty of ±30%; two colons, ±50%; and three colons, ±100%. A line with no comment or a

[1]IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.

comment containing no colons is assumed to have an uncertainty of ±10%. Uncertainties can also be input using an "uncertainty file" – a text file containing the wavelength of the line in one column and the flux uncertainty in CGS flux units in the second column. Wavelengths in these files are matched to the reference wavelengths via the same method used for splot log files. Thus it is possible to use the same observed wavelengths for this file as are used in the splot log file, or to use the intended reference wavelength to be matched directly.

4.4.1. convert_data

The convert_data task provides a simple method of preparing data from an arbitrary format to the same text layout as an splot data file. The user must provide the input text file and a string describing the existing format; a command line would look like this:

```
$ elsa convert_data data_file output_file format_string.
```

As an example, consider data exported from a spreadsheet program in csv (comma separated values) format. In plain text, this data file, called data1.csv, might look like:

```
Name,Wavelength,Flux,Notes
He II,4686,1.1
H beta,4861,100
[O III],5007,1105,(forbidden)
H alpha,6563,289
```

To convert this data to splot_log format, run the command:

```
$ elsa convert_data data1.csv data1.convert.log c,w,f,
```

ELSA would read "c,w,f," as the format string and recognize the first column as a comment, the second as the wavelength, the third as the flux, and ignore the fourth. This data would be saved in data1.convert.log, ready to be analyzed by ELSA. By changing the format string, nearly any regular table of data can be interpreted by ELSA. There is also an option to facilitate the reading of tables from TeX files, to make analysis of previously published results easy. For a full explanation of the convert_data task, see the ELSA documentation.

4.4.2. splot_undup

The splot_undup task searches through a single input data file to find multiple instances of the same line. Two entries in the data file are considered to be instances of the same line if they fall within the wavelength tolerance parameter. ELSA will prompt the user interactively to select which one of the data entries to use. Comments, uncertainties (if available) and continuum levels are displayed to assist in this selection process. After all selections have been made, a file containing only single instances of each line is written as output. The generic command line would look like this:

```
$ elsa splot_undup input_file output_file.
```

4.4.3. normalize

The normalize task is used to aid in the combining an object's optical spectrum with an ultraviolet or infrared spectrum. First, both spectra are read in and prepared in the normal way (dereddening, etc.); this includes any extragalactic corrections, if they are set in the configuration file. Then ELSA looks for pairs of lines in the two spectra: hydrogen lines if the second spectrum is in the infrared, and ionized helium lines if the second spectrum is in

the ultraviolet data. The correct ratio for the relevant pair is calculated using intrat, which requires a temperature and density; these can either be directly supplied as command line arguments, or else strings may be given indicating what to calculate and use in the same manner as for temp_dens (see §5.4). The normalize task then calculates the expected line strength ratio of the pair, and presents as its output a scale factor to be applied to the non-optical spectrum, which is accomplished through the splot_merge task (§4.4.4).

To combine an infrared spectrum with an optical one, either the H I 7.46 μm (6-5) or the 12.4 μm (7-6) line can be used. To combine an ultraviolet spectrum with an optical one, the He II λ1640 line is required. If the relevant line(s) is absent from the non-optical spectrum, normalize will fail. Likewise, Hβ is required in the optical spectrum for combining with infrared data, and He II λ4686 for combining with ultraviolet data. Finally, if no temperature or density is provided or requested (that is, no fourth or fifth arguments given) then these diagnostics are calculated from the optical data as in normal ELSA usage (and ELSA will tell you which temperature and density are being used). The generic command would look like this:

```
$ elsa normalize optical_file UV_or_IR_file radial_velocity temperature density
```

4.4.4. splot_merge

The splot_merge task functions similarly to splot_undup, except that its pool of input data is drawn from two separate input files instead of a single input file. Multiple instances of a line are identified whether originating in a single file or across both files. The user must specify a pre-calculated scale factor by which the second file's data are to be multiplied to match the first file. This often happens when, for example, an object's spectrum is obtained in two observations, with a region of wavelength overlap from which the scale factor can be

determined.

As above, the user is prompted interactively to choose which of multiple measurements of the same line to write into the merged output file. The source data file name, wavelength, flux, and flux uncertainty are displayed in this process. The resulting output file contains all single instances of lines identified in both input files, appropriately scaled and sorted by wavelength. The generic command line would look like this:

$ elsa splot_merge file1 file2 scale output_file.

4.4.5. splot_flag

The splot_flag task is primarily meant as a diagnostic tool. It produces plain text output containing a list of all lines in the input file that did *not* match any line in the reference list as well as all lines with long comments. This is meant to aid in identifying lines that should have been identified but were not, or lines where an otherwise overlooked comment may provide additional insight into how to handle it. The generic command line would look like this:

$ elsa splot_flag input_file radial_velocity output_file.

4.5. Output

ELSA's two major functions are to produce a well-formatted table of wavelengths, fluxes, and corrected, scaled intensities relative to Hβ, and to compute plasma diagnostics and abundances of a variety of elements and their component ionization stages. These two operations are supported by the splot_table and splot_abun tasks, described below.

Both tasks can produce output as a LaTeX source file which is meant to be suitable for publications using the AASTeX macro set[2], or as a plain text file. Note that this text file output normally contains a header row, which can be suppressed with a command line option, thereby producing purely tabular output readable by a host of graphing and plotting software.

4.5.1. splot_table

The splot_table task produces an organized table of line identifications, wavelengths, fluxes, corrected and scaled intensities relative to Hβ and the uncertainties in those intensities, if error propagation is enabled. The input is an splot log file, the object's radial velocity (needed to redshift-correct the wavelengths to match them with the reference list), its external uncertainty file (if applicable) and an output file name. The command might look like this:

```
$ elsa splot_table splot_logfile radial_velocity output_file.
```

Final values may be output as a table in either LaTeX source format, CSV (comma separated value, suitable for reading into Excel and other spreadsheet software) or plain text format (See Table 2 in Appendix B). Several objects may be combined into a "composite" table, which adds extra columns as appropriate (see documentation).

[2]http://www.journals.uchicago.edu/AAS/AASTeX/docs.html

4.5.2. splot_abun

The splot_abun task provides an interface to ELSA's five-level atom code. It takes an splot log file as input, including a radial velocity for redshift corrections, an external error file (if applicable) and an output file. Abundances are computed as described in §4. Output is available as a LaTeX source file. A typical command line would look like:
$ elsa splot_abun input_file radial_velocity output_file.

Several objects may be combined into a "composite" table, which adds extra columns (see documentation).

5. The Calculations

ELSA contains a sophisticated extinction correction scheme that takes into account various contamination and environmental effects on lines used in the correction. It includes an abundance calculation facility based on the five-level atom model using the most recent atomic data. Tools are also provided to make updating and integrating new atomic data very straightforward.

ELSA is capable of two kinds of output: formatted tables of observed and extinction- and contamination-corrected line fluxes, and formatted tables of ionic and elemental abundances (including temperatures and densities used in determining those abundances). Both kinds of output are available for an individual object or a group of objects. Supported output formats are LaTeX, plain text, and CSV tables readable by Excel.

5.1. Reddening/He^+ Contamination Loop

We assume that a properly formatted input file has been created using one or more of the tasks described in §4. The user would generally now proceed have ELSA correct the line fluxes for interstellar extinction and produce a well-formatted table of the results. The extinction correction uses a standard reddening law dependent on the wavelength region. The current version of ELSA supports corrections for ultraviolet, visible, and infrared observations. For the ultraviolet we use the reddening law of **?**, for the optical, we use **?** and for the infrared, **?**. For the dereddening process to be successful, accurate determinations of particular reference lines are needed; in the visible the hydrogen Balmer lines are typically used. In this case ELSA has the ability to compute the dereddening constant c, using Hβ as the reference line:

$$c = \log_{10}\left(\frac{F(\mathrm{H}\alpha)}{aF(\mathrm{H}\beta)}\right)\frac{1}{f(\lambda)}$$

where a represents the ideal ratio of Hα/Hβ and $f(\lambda)$ represents the wavelength-dependent reddening law (which in this example would be evaluated at λ6563). The user can choose to use Hγ/Hβ or Hδ/Hβ as the reference ratio for this correction by suitably editing ELSA's configuration file.

A number of additional effects can be considered by ELSA to determine the value of c. The ratio a depends on the electron temperature and density of the object. It is often standard to set $a = 2.86$, which is correct only in the case $T_e \sim 10,000$ K and $N_e \sim 100$ cm^{-3}. ELSA begins with a user-specified seed value (the canonical value of 2.86 is the default) to find a first-pass c and to correct the [O III] λ4363/λ5007 lines and the [S II] λ6716/λ6731 lines, which are then used to find $T_{[O\ III]}$ and $N_{[S\ II]}$. We based the code and process for subsequently obtaining the ratio a on INTRAT, as described in Storey & Hummer (1995). The new value of a is used to compute a preliminary value for the He II λ4686 line. This allows us, using the same line ratio regression method, to find the line

strengths of the ionized helium Pickering series lines which underlie the hydrogen Balmer lines.

The corrected hydrogen Balmer lines and the revised value of a are then used to find a new value of c. The program then proceeds to deredden the original line flux values using the new c. It is then possible to use newly-derived temperatures and densities to find a new value of a, and so on until successive values of a converge. Once the final value of a is found, a final c is computed. The correction is then applied to all input lines to find the *intensity*,

$$I(\lambda) = 100 \left(\frac{F(\lambda)}{F(\mathrm{H}\beta)} \right) 10^{cf(\lambda)}.$$

Certain configuration file options affect the behavior of this process. The user may opt not to find new values of a. In this case, there is only one iteration of the loop, in which only the seed value of a is used. The user may impose a single value of c for all dereddening operations, or the user may disable the dereddening process entirely.

5.2. Deblending Unresolved Lines

ELSA's standard line list contains several instances where a diagnostically useful line is blended with another line too close in wavelength to be resolved: Hα with He II λ6560, [S III]λ6312 with He II λ6310, Hβ with He II λ4859, Hγ/ with He IIλ4339, Hδ with He II λ4101, and Hϵ with [Ne III] λ3968 (and He II λ3968, which we do not correct for). Using the "deblend" option in the configuration file instructs ELSA to calculate the expected intensity of the weaker contaminant based on related line strengths and nebular conditions, and to subtract it from the intensity of the blended pair, yielding in each case the intensity of each component separately. Tabulated values for these lines are notated in the flux tables with a superscript *a*.

5.3. Extragalactic Applications

Although ELSA was originally designed to process data from planetary nebulae, it has been adapted to handle from extragalactic HII regions, blue compact dwarf galaxies, AGNs, and any other object which resides in a host galaxy. The main concern for these types of objects is the underlying stellar absorption spectrum superposed onto the emission line spectrum by the host galaxy.

In order to account for this, ELSA attempts to determine the amount of absorption present. It calculates values of the reddening factor $c_{\mathrm{H}\beta}$ based on the three main Balmer line ratios, Hα/Hβ, Hγ/Hβ and Hδ/Hβ, assuming various levels of absorption (as equivalent widths in Å). The user may choose the maximum absorption estimate and the spacing of the rows in the table. Formal errors are computed for each entry in the table. The errors are based on assumed error of $\pm$10% in the absorption estimate, as well as the error in the parameters used to find $c_{\mathrm{H}\beta}$. Users are prompted to enter their best scientific estimate of what the actual amount of absorption is (generally, where the $c_{\mathrm{H}\beta}$ agrees for all three ratios). The absorption is understood to be constant, in terms of equivalent width, for all Balmer lines.

While ELSA contains many deeply iterative processes, the absorption selection is only made on the first pass. This is because the interactivity of the process makes it unreasonable to repeat many times, and because absorption is generally not dependent on other factors and is unlikely to change with further iteration of the loops.

Once the user has chosen an appropriate level of absorption, the equivalent amount in flux units is added to each line. This then becomes the "original" flux used for future dereddening loops and for reporting line strengths relative to Hβ.

5.4. Plasma Diagnostics and Abundances

ELSA calculates electron temperatures and densities, ionic abundances, and total elemental abundances from measured line strengths using the incorporated program ABUN (written by R.B.C.H.), which features a five-level atom routine, along with ionization correction factors (ICF) as described in **?** and **?**. ELSA uses a two-region ionization model with the [O III] temperature used to account for higher ionization regions and [N II] for lower ionization regions. Future work may include adding an [Ar IV] temperature to account for higher ionization regions than are represented by [O III]. Table 1 summarizes the ions currently included in ELSA, the wavelengths of the emission line(s) used to obtain the ionic abundances, and the temperatures and densities used in the calculations. In the event that one or more of the standard diagnostic ratios for $T_{[O\ III]}$, $T_{[N\ II]}$ or $N_{[S\ II]}$ is not available, default values can be inserted into the configuration file. If either $T_{[O\ III]}$ or $N_{[S\ II]}$ is not able to be calculated, then the correction loop described in §5.1 will not run and the selected Balmer ratio (specified in the configuration file) defaults to the value specified in the program at compile time.

Ionic abundances are calculated directly from line strengths; the former are then added together and their sum multiplied by an appropriate ICF, i.e., the ratio of total elemental abundance to the sum of observable ions, to correct for unseen ions. This procedure can be expressed analytically for the number abundance of element X as follows:

$$N(X) = \left\{ \sum^{obs} \frac{I_\lambda}{\epsilon_\lambda(T_e, N_e)} \right\} \cdot ICF(X). \tag{1}$$

Since we are interested in determining ionic abundances with respect to H^+, I_λ is entered as a value normalized with respect to Hβ, and hence an Hβ generation rate is included in the denominator of Eq. 1.

The sources for atomic data used for computing the abundance of each ion are noted in a file distributed with ELSA and can be included in LaTeX output if desired. Python scripts are provided to facilitate automated updating of the atomic data using the online data repository of The Iron Project (**?**) as well as rebuilding the local references database to keep it current with new data; see §7.

ELSA also includes a convenient quick task for calculating temperatures and densities. Typing:

```
$ elsa temp_dens
```

yields the following prompt:

> Please enter densities and temperatures to calculate, one per line, followed by a blank line: (Format example: 'dens S2' for Sulfur II density, 'temp O3' for Oxygen III temperature) Currently available temperatures and densities:
> temp O2 dens S2
> temp O3 dens Cl2
> temp N2 dens Cl3
> temp S2 dens Ar3
> temp S3 dens S3
> dens Ne5
> dens Ne3

The user is then further prompted to enter the requisite line intensities for the chosen calculation, results of which are displayed on the screen.

5.5. Uncertainty Propagation

ELSA includes a routine to propagate uncertainties through to the final results. These can include uncertainties in line fluxes, reddening correction, plasma diagnostics, and ionic abundances. Upon command, ELSA can produce uncertainty values for the calculated line intensities and the final elemental abundances.

To estimate the uncertainly in the final results, ELSA adds the contributing uncertainties in quadrature. We can think of any output value y_i (intensity or abundance) as being calculated by a function $F(x_1, x_2, x_3, \ldots)$, where the parameters are the line data. If each parameter x_j has an uncertainty σ_j , the uncertainty σ_i for y_i can be calculated using the equation

$$\sigma_i^2 = \sigma_1^2(\partial x_1/\partial y_i)^2 + \sigma_2^2(\partial x_2/\partial y_i)^2 + \ldots \quad (2)$$

To implement this, ELSA iteratively calculates numerical partial derivatives. In other words, it varies each input variable x_j several times, until the partial derivative $\partial x_j/\partial y_i$ converges for each output value y_i. These partial derivatives, when added together as in eq. 10, produce accurate uncertainty values for all output values.

As the task executes, screen output scrolls though the input lines. Although this method is time-intensive, ELSA is efficient enough for it to be useful. For the example in §3, running splot_abun with uncertainty calculations on an Intel Macintosh Pro dual core machine added about 100 seconds to the 2-second job without them.

6. Limitations and Testing

ELSA does not currently include abundance calculations for ionic abundances of metals, e.g., magnesium, silicon, iron. In addition, the current version of ELSA applies a two-zone ionization model described by either $T_{[O\ III]}$ or $T_{[N\ II]}$. In the future (see §8) we

plan to add a higher ionization zone using $T_{[Ar\ IV]}$.

We have tested ELSA in three ways. First, using identical reddening-corrected input line strengths for a sample of planetary nebulae of various Peimbert types and excitations, we have compared temperatures, densities and ionic abundances of O, N, Ne, S, Ar, and Cl calculated by ELSA with results calculated by the *nebular* package (**?**). Overall the agreement is quite good. In the instances where a discrepancy appears, at least some of the difference is likely due to the use of different atomic constants or interpolation routines.

Second, we have used ELSA to analyze the sample of H II regions in M101 from **?** that were originally analyzed with *nebular*. The agreement for $T_{[O\ III]}$ is nearly exact. We compared ionic and total abundances of O, N, Ne, S, Ar, and Cl, and except for the cases where there was no [N II] λ5755, and ELSA's default $T_{[N\ II]}$ was clearly too low, the ionic abundance agreement is again quite good, and the slight systematic differences are traceable to different atomic constants and/or different ionization correction factors.

Third, we have taken the predicted line intensities from a series of CLOUDY (**?**) models of planetary nebulae having different metallicities, densities, stellar temperatures and luminosities, and used ELSA to try to reproduce the input abundances. We discovered that just as it is often impossible to fit every measured intensity and flux ratio from a real nebula with a single CLOUDY model, it is likewise difficult to exactly recover the input abundances from CLOUDY's output spectrum. Overall agreement for ionic abundances at solar and half-solar metallicity is $\sim$ 25%, with the exception of the S^+/H^+ abundance for which ELSA's values are systematically lower than CLOUDY's by $\sim$40%.

The most extreme disagreement we found was at halo metallicity with a stellar temperature of 150,000 K, where ELSA's ionic abundances are all above CLOUDY's by $\sim$40%, except for S^+/H^+, which is $\sim$80% lower than CLOUDY's. As an independent check, we analyzed several of the CLOUDY models using *nebular*. We found comparable results

in all cases, including at halo metallicity with a stellar temperature of 150,000 K, where *nebular*'s ionic abundances are all larger than CLOUDY's, and S^+/H^+ is again, significantly smaller. Overall agreement with CLOUDY's input abundances is slightly better with ELSA, except for the S^+/H^+ disparity which is slightly less extreme with *nebular*. We have ruled out charge exchange or the use of different atomic data as the cause of this S^+/H^+ discrepancy, and conclude that it must arise from the assignment of different temperatures to the S^+ region, with ELSA's and *nebular*'s being higher than CLOUDY's. This issue may be related to the *sulfur anomaly* in planetary nebulae as described in **?**, and two of us (Henry & Kwitter) are actively investigating this effect.

In sum, all of these tests, plus internal consistency checks give us confidence that ELSA is an effective tool for nebular abundance studies.

7. Updating Atomic Constants

Included with the ELSA source code are two Python scripts designed to update the atomic constants used by ELSA. The first one, elsa_gettipbaseconstants.py, downloads the latest atomic constants from The Iron Project (http://vizier.u-strasbg.fr/tipbase/home.html). The second, elsa_merge_constants.py, puts those constants into the ELSA code, with an option to use only the original constants instead. ELSA must then be recompiled. The command sequence is thus:

```
$ elsa_merge_constants.py -t
$ make clean; make
```

Atomic constants do not need to be updated frequently, but only when new data are added into TIPBASE. Finally, references for the atomic data used by ELSA can be obtained through ELSA's references task. Full usage information for this can be found in ELSA's

documentation.

8. Future Plans

For the next release of ELSA we plan several additions. To incorporate a three-zone ionization model, we will be adding a higher-ionization zone characterized by $T_{[Ar\ IV]}$; to achieve this, we will be implementing neutral helium intensity calculations by **?** so that we can accurately deblend He I λ4713 from [Ar IV] λ4711. We also plan to add a two-level atom calculation that will enable us to derive some ionic abundances for metals **Jesse - which?**. And finally, we hope to implement a references task that will produce on command a list of the atomic data sources used in ELSA's calculations.

9. Acknowledgments

This project was begun when M.J.D. was a Keck Northeast Astronomy Consortium (KNAC) summer fellow at Williams College in 2005, and continued in 2006 when P.J.J.O'M was a KNAC summer fellow at Williams. This are grateful to to the National Science Foundation for its support of KNAC through Grant No. AST-0353997. We also thank Peter Nunns (Williams '08) who volunteered his time during the summer of 2006 to work on the error propagation portion of ELSA, and Steven Souza for his time and his clear-headed advice.

A. *splot* log files for IC 5217

5217blue.txt:

Mar 28 13:56 [IC5217]: IC 5217

center cont flux eqw core gfwhm lfwhm

3726.176 1.874E-14 9.807E-13 -52.91

3751.799 1.633E-14 1.344E-13 -8.218

3769.85 1.534E-14 1.351E-13 -8.772

3797.089 1.171E-14 2.417E-13 -20.69

3834.22 9.214E-15 3.374E-13 -36.64

center cont flux eqw core gfwhm lfwhm

3867.354 8.989E-15 5.189E-12 -577.2 6.687E-13 7.289 0.

3887.247 6.592E-15 9.736E-13 -147.7 1.255E-13 7.289 0.

center cont flux eqw core gfwhm lfwhm

3966.448 8.737E-15 2.338E-12 -269.

4024.474 9.121E-15 1.122E-13 -12.29

4067.908 1.021E-14 7.514E-14 -7.356

4099.639 1.039E-14 1.356E-12 -130.8

4338.396 7.080E-15 2.403E-12 -339.4

4361.296 6.293E-15 6.222E-13 -97.92

4469.428 6.674E-15 2.760E-13 -41.27

4683.718 5.950E-15 5.226E-13 -88.43

4709.501 5.642E-15 2.903E-13 -51.64

4738.081 5.512E-15 2.558E-13 -46.45

4859.155 5.763E-15 5.641E-12 -973.5

4919.901 6.820E-15 6.639E-14 -9.756

4956.707 9.399E-15 2.327E-11 -2475.

5004.6 5.643E-15 7.072E-11 -12532.

5199.034 7.441E-15 5.595E-15 -0.7513

5408.637 6.227E-15 5.995E-14 -9.632

5514.726 7.260E-15 2.482E-14 -3.42

5514.825 7.303E-15 2.391E-14 -3.41

5534.979 6.292E-15 3.439E-14 -5.467

5751.565 5.988E-15 5.142E-14 -8.582

5872.604 6.496E-15 9.704E-13 -149.2

6097.704 6.382E-15 7.244E-15 -1.135

center cont flux eqw core gfwhm lfwhm

6297.31 5.282E-15 1.327E-13 -25.13 1.465E-14 8.512 0.

6309.226 5.213E-15 1.094E-13 -20.99 1.208E-14 8.512 0.

center cont flux eqw core gfwhm lfwhm

6360.973 6.063E-15 3.303E-14 -5.453

center cont flux eqw core gfwhm lfwhm

6544.403 -3.42E-15 6.409E-13 INDEF 8.008E-14 7.518 0.

6559.684 -3.42E-15 1.999E-11 INDEF 2.497E-12 7.518 0.

6580.389 -3.42E-15 1.753E-12 INDEF 2.191E-13 7.518 0.

center cont flux eqw core gfwhm lfwhm

6675.257 5.258E-15 2.833E-13 -53.87

center cont flux eqw core gfwhm lfwhm

6713.192 5.790E-15 9.222E-14 -15.93 1.123E-14 7.714 0.

6727.708 5.910E-15 1.799E-13 -30.45 2.191E-14 7.714 0.

5217red.txt

Here is the Ha to use

Jan 26 20:14 [IC5217[*,1,1]]: IC 5217

center cont flux eqw core gfwhm lfwhm

6544.888 2.021E-15 5.416E-13 -268.1 6.008E-14 8.469 0.

6560.083 -8.20E-16 2.046E-11 INDEF 2.269E-12 8.469 0.

6580.635 -4.66E-15 1.803E-12 INDEF 2.000E-13 8.469 0.

center cont flux eqw core gfwhm lfwhm

5753.327 6.428E-15 4.134E-14 -6.428

5873.452 5.382E-15 9.533E-13 -175.2

6100.224 5.438E-15 1.575E-14 -2.896

center cont flux eqw core gfwhm lfwhm

6297.479 5.030E-15 1.167E-13 -23.2 1.130E-14 9.704 0.

6309.377 4.969E-15 1.065E-13 -21.44 1.031E-14 9.704 0.

center cont flux eqw core gfwhm lfwhm

6361.526 5.673E-15 3.189E-14 -5.614

6675.253 5.732E-15 2.827E-13 -49.32

center cont flux eqw core gfwhm lfwhm

6713.052 5.643E-15 1.111E-13 -19.69 1.118E-14 9.332 0.

6727.748 5.611E-15 2.111E-13 -37.63 2.125E-14 9.332 0.

center cont flux eqw core gfwhm lfwhm

7062.016 5.417E-15 4.187E-13 -77.2

7002.273 5.426E-15 5.794E-15 -1.068

7132.464 5.669E-15 8.885E-13 -156.5

7258.439 4.900E-15 1.103E-14 -2.252

7278.412 4.865E-15 5.331E-14 -10.95

7321.159 5.068E-15 3.174E-13 -62.62

7526.761 5.426E-15 3.969E-14 -7.316

7747.587 5.246E-15 2.252E-13 -42.85

8041.534 5.301E-15 8.370E-14 -15.73

8233.645 4.413E-15 1.772E-14 -4.012

8464.306 3.008E-15 2.609E-14 -8.677

8498.063 2.782E-15 4.614E-14 -16.62

8541.247 2.856E-15 5.538E-14 -19.39

8594.422 2.929E-15 5.975E-14 -20.41

8660.645 2.982E-15 9.335E-14 -31.33

8746.311 3.274E-15 1.003E-13 -30.85

8858.925 3.447E-15 1.308E-13 -38.07

9010.059 3.110E-15 1.365E-13 -43.92

9064.55 3.584E-15 1.953E-12 -545.7

9224.708 3.717E-15 2.396E-13 -65.03

center cont flux eqw core gfwhm lfwhm

9526.379 3.347E-15 2.986E-12 -892.1 2.795E-13 10.04 0.

9541.591 2.708E-15 3.750E-13 -138.5 3.510E-14 10.04 0.

all lines like Pa and Cl and Ar IV are weak

B. Formatted Tables of Line Measurements: LaTeX and Plain Text

Table 1. Fluxes and Intensities

		5217	
Line	f(λ)	F(λ)	I(λ)
[O II] λ3727	0.292	17.5	21.0
He II + H11 λ3770	0.280	2.41	2.87
He II + H10 λ3797	0.272	4.30	5.11
He II + H9 λ3835	0.262	6.01	7.09
[Ne III] λ3869	0.252	92.4	108
He I + H8 λ3889	0.247	17.3	20.2
[Ne III] λ3968	0.225	27.7[a]	31.9[a]
Hϵ λ3970	0.224	14.0[a]	16.1[a]
He I + He II λ4026	0.209	2.00	2.28
[S II] λ4071	0.196	1.34	1.51
He II λ4100	0.188	0.114[a]	0.128[a]
Hδ λ4101	0.188	24.0[a]	27.1[a]
He II λ4339	0.124	0.210[a]	0.227[a]
Hγ λ4340	0.124	42.6[a]	46.0[a]
[O III] λ4363	0.118	11.1	11.9
He I λ4472	0.090	4.92	5.20
He II λ4686	0.036	9.31	9.52
He I + [Ar IV] λ4711	0.030	5.17	5.27
[Fe III] λ4734	0.024	4.56	4.63

Table 1—Continued

		5217	
Line	f(λ)	F(λ)	I(λ)
[Ar IV] λ4740	0.023	4.56	4.62
He II λ4859	0.000	0.469[a]	0.469[a]
Hβ λ4861	0.000	100[a]	100[a]
He I λ4922	-0.021	1.18	1.17
[O III] λ4959	-0.030	414	407
[O III] λ5007	-0.042	1260	1227
[N I] λ5199	-0.086	9.96(-2)	9.44(-2)
He II λ5412	-0.134	1.07	0.982
[Cl III] λ5518	-0.157	0.442	0.400
[Cl III] λ5538	-0.161	0.613	0.553
[N II] λ5755	-0.207	0.916	0.804
He I λ5876	-0.231	17.3	14.9
[K IV] λ6102	-0.276	0.129	0.108
[O I] λ6300	-0.313	2.36	1.94
He II λ6311	-0.315	4.14(-2)[a]	3.39(-2)[a]
[S III] λ6312	-0.315	1.91[a]	1.56[a]
[O I] λ6364	-0.325	0.588	0.479
[N II] λ6548	-0.358	11.4	9.11
He II λ6560	-0.360	1.61[a]	1.29[a]

Table 1—Continued

		5217	
Line	f(λ)	F(λ)	I(λ)
Hα λ6563	-0.360	354[a]	282[a]
[N II] λ6584	-0.364	31.2	24.8
He I λ6678	-0.380	5.05	3.97
[S II] λ6716	-0.387	1.64	1.29
[S II] λ6731	-0.389	3.20	2.51
[Ar V] λ7006	-0.433	0.103	7.86(-2)
He I λ7065	-0.443	7.46	5.64
[Ar III] λ7136	-0.453	15.8	11.9
O I λ7255	-0.471	0.196	0.146
[Ar IV] λ7263	-0.472	0.196	0.146
He I λ7281	-0.475	0.949	0.704
[O II] λ7324	-0.481	5.65	4.18
[Cl IV] λ7531	-0.510	0.707	0.513
[Ar III] λ7751	-0.539	4.01	2.86
[Cl IV] λ8046	-0.574	1.49	1.04
He II λ8237	-0.595	0.316	0.217
P16 λ8467	-0.618	0.465	0.315
[Cl III] + P15 λ8501	-0.622	0.822	0.556
P14 λ8545	-0.626	0.986	0.665

Table 1—Continued

	5217	
Line	f(λ)	F(λ)	I(λ)
P13 λ8598	-0.631	1.06	0.715
P12 λ8665	-0.637	1.66	1.11
P11 λ8750	-0.644	1.79	1.19
P10 λ8863	-0.654	2.33	1.54
P9 λ9015	-0.666	2.43	1.60
[S III] λ9069	-0.670	34.8	22.8
P8 λ9228	-0.610	4.27	2.91
[S III] λ9532	-0.632	53.2	35.7
P7 λ9546	-0.633	6.68	4.48
c			0.27
Hα/Hβ			2.82
log $F_{H\beta}$[b]		-11.25	

[a]Deblended.

[b]ergs cm^{-2} s^{-1} in our extracted spectra

Table 2

Name lambda f(lam) F(lam) I(lam)

[O II] 3727.0 0.292 17.5 21.0

He II + H11 3770.0 0.280 2.41 2.87

He II + H10 3797.0 0.272 4.30 5.11

He II + H9 3835.0 0.262 6.01 7.09

[Ne III] 3868.8 0.252 92.4 108

He I + H8 3889.0 0.247 17.3 20.2

[Ne III] 3968.0 0.225 27.7 31.9

H epsilon *3970.1 0.224 14.0 16.1

He I + He II 4026.0 0.209 2.00 2.28

[S II] 4071.0 0.196 1.34 1.51

He II *4100.0 0.188 0.114 0.128

H delta 4101.0 0.188 24.0 27.1

He II *4338.7 0.125 0.210 0.227

H gamma 4340.5 0.124 42.6 46.0

[O III] 4363.2 0.118 11.1 11.9

He I 4471.5 0.090 4.92 5.20

He II 4685.7 0.036 9.31 9.52

He I + [Ar IV] 4711.0 0.030 5.17 5.27

[Ar IV] 4740.2 0.023 4.56 4.62

He II *4859.3 -0.006 0.469 0.469

H beta 4861.3 0.000 100 100

He I 4921.9 -0.021 1.18 1.17

[O III] 4958.9 -0.030 414 407

[O III] 5006.8 -0.042 1260 1227

[N I] 5199.0 -0.086 9.96(-2) 9.44(-2)

He II 5411.5 -0.134 1.07 0.982

[Cl III] 5517.7 -0.157 0.442 0.400

[Cl III] 5537.6 -0.161 0.613 0.553

[N II] 5754.6 -0.207 0.916 0.804

He I 5875.7 -0.231 17.3 14.9

[K IV] 6101.8 -0.276 0.129 0.108

[O I] 6300.3 -0.313 2.36 1.94

He II *6310.8 -0.315 4.14(-2) 3.39(-2)

[S III] 6312.0 -0.315 1.91 1.56

[O I] 6363.8 -0.325 0.588 0.479

[N II] 6548.1 -0.358 11.4 9.11

He II *6560.0 -0.360 1.61 1.29

H alpha 6563.0 -0.360 354 282

[N II] 6583.5 -0.364 31.2 24.8

He I 6678.2 -0.380 5.05 3.97

[S II] 6716.4 -0.387 1.64 1.29

[S II] 6730.8 -0.389 3.20 2.51

[Ar V] 7005.7 -0.433 0.103 7.86(-2)

He I 7065.2 -0.443 7.46 5.64

[Ar III] 7135.8 -0.453 15.8 11.9

[Ar IV] 7262.8 -0.472 0.196 0.146

He I 7281.4 -0.475 0.949 0.704

[O II] 7324.0 -0.481 5.65 4.18

[Cl IV] 7530.5 -0.510 0.707 0.513

[Ar III] 7751.1 -0.539 4.01 2.86

[Cl IV] 8045.6 -0.574 1.49 1.04

He II 8236.8 -0.595 0.316 0.217

P16 8467.3 -0.618 0.465 0.315

[Cl III] + P15 8501.0 -0.622 0.822 0.556

P14 8545.4 -0.626 0.986 0.665

P13 8598.4 -0.631 1.06 0.715

P12 8665.0 -0.637 1.66 1.11

P11 8750.5 -0.644 1.79 1.19

P10 8862.8 -0.654 2.33 1.54

P9 9015.0 -0.666 2.43 1.60

[S III] 9069.2 -0.670 34.8 22.8

P8 9228.0 -0.610 4.27 2.91

[S III] 9532.0 -0.632 53.2 35.7

P7 9546.0 -0.633 6.68 4.48

c = 0.27

Ha/Hb = 2.82

log F(Hb) = -11.25

* = deblended

C. LaTeX Formatted Abundances, Including Uncertainties

Table 1. Ionic Abundances

	5217	
Ion	T_{used}	Abundance
He^{+}	[O III]	9.76±1.31(-2)
He^{+2}	[O III]	8.79±1.32(-3)
icf(He)		1.00
O^{0}(6300)	[N II]	*1.67±0.66(-6)
O^{0}(6363)	[N II]	*1.29±0.51(-6)
O^{0}	wm	1.59±0.63(-6)
O^{+}(3727)	[N II]	*6.84±5.62(-6)
O^{+}(7325)	[N II]	*6.75±3.13(-6)
O^{+}	wm	6.82±4.70(-6)
O^{+2}(5007)	[O III]	*2.90±0.73(-4)
O^{+2}(4959)	[O III]	*2.77±0.56(-4)
O^{+2}(4363)	[O III]	*2.90±0.73(-4)
O^{+2}	wm	2.87±0.67(-4)
icf(O)		1.09±0.02
Ar^{+2}(7135)	[O III]	*8.41±1.93(-7)
Ar^{+2}(7751)	[O III]	*8.37±2.13(-7)
Ar^{+2}	wm	8.40±1.91(-7)
Ar^{+3}(4740)	[O III]	*5.50±1.11(-7)
Ar^{+4}(7005)	[O III]	*1.21±0.29(-8)
icf(Ar)		1.11±0.03

Table 1—Continued

	5217	
Ion	T_{used}	Abundance
Cl^{+2}	[S III]	5.43±1.52(-8)
Cl^{+2}(5517)	[S III]	*6.20±3.05(-8)
Cl^{+2}(5537)	[S III]	*4.98±1.14(-8)
Cl^{+2}	wm	5.49±1.70(-8)
Cl^{+3}(8045)	[O III]	6.40±1.68(-8)
icf(Cl)		1.09±0.02
N^{+}(6584)	[N II]	*3.14±1.08(-6)
N^{+}(6548)	[N II]	*3.39±1.09(-6)
N^{+}(5755)	[N II]	*3.14±1.08(-6)
N^{+}	wm	3.20±1.07(-6)
icf(N)		46.9±30.55
Ne^{+2}(3869)	[O III]	*6.81±1.63(-5)
Ne^{+2}(3967)	[O III]	6.65±2.03(-5)
icf(Ne)		1.12±0.03
S^{+}	[N II]	*1.30±0.94(-7)
S^{+}(6716)	[N II]	1.30±0.95(-7)
S^{+}(6731)	[N II]	1.30±0.94(-7)
S^{+}	[S II]	2.09±3.94(-7)
S^{+2}(9069)	[S III]	*2.48±0.82(-6)
S^{+2}(6312)	[S III]	*2.48±0.82(-6)

Table 1—Continued

	5217	
Ion	T_{used}	Abundance
S^{+2}	wm	2.48±0.82(-6)
icf(S)		1.99±0.62

Table 2. Temperatures and Densities

	5217	
Parameter	Value	Notes
$T_{[OIII]}$	11360±623	
$T_{[NII]}$	13350±2049	
$T_{[OII]}$	13200±9763	
$T_{[SII]}$	9554±7156	
$T_{[SIII]}$	11070±1080	Used 9069.
$Ne_{[SII]}$	8219±7503	
$Ne_{[ClIII]}$	4934±1692	

Table 3. Total Elemental Abundances

Parameter	5217	Solar Ref	Orion Ref
He/H	0.106±0.013	9.80(-2)	9.80(-2)
N/H	1.50±0.68(-4)	9.33(-5)	6.03(-5)
N/O	0.470±0.207	0.130	0.110
O/H	3.20±0.74(-4)	7.41(-4)	5.25(-4)
Ne/H	7.59±1.85(-5)	1.20(-4)	7.76(-5)
Ne/O	0.237±0.038	0.160	0.150
S/H	5.18±2.29(-6)	2.14(-5)	1.48(-5)
S/O	1.62±0.75(-2)	2.90(-2)	2.80(-2)
Cl/H	5.99±1.84(-8)	3.16(-7)	2.14(-7)
Cl/O	1.87±0.57(-4)	4.26(-4)	4.08(-4)
Ar/H	1.56±0.27(-6)	3.31(-6)	3.09(-6)
Ar/O	4.88±0.79(-3)	4.47(-3)	5.89(-3)

D. Default Configuration File

```
# This is the elsa config file. Comments begin with pound signs.


# File name of the spec file, which contains a return-delimited list of
# recognized theoretical wavelengths, in angstroms. The path to the file
# must be absolete or relative to the directory that pne runs from.
# Note: Don't put H-alpha or H-beta's wavelegnths in this file;
# specify them below.

WavelengthFile wavelengths.txt


# Maximum number of wavelengths elsa will read out of your
# wavelength spec file. Make sure you set it high enough to scoop up
# all your wavelengths.

MaxWavelengths 512


# Maximum tolerance (in angstroms) for identifying observed wavelengths
# with a theoretical wavelength from the spec file. (For example, if you
# set this to 3, a wavelength of 6565.5 will identify with the H-alpha line,
# assume it's listed as 6563). If this is set high enough that an observed
# wavelength "qualifies" for multiple spec wavelengths, it will default to
# the first (lowest) wavelength, which is most likely not what you want,
# so make sure your choice coincides with your data. This value may be set
```

to a floating point value if need be.

MaxTolerance 4.0

MaxToleranceIR 750.0

Wavelengths (in angstroms) of H-alpha and H-beta. These are used for

calculating the extinction constants and internal abundance ratios.

You most likely want to keep them at 6563 and 4861 respectively,

unless you really know what you're doing and need to change them.

These can be floating point values.

HalphaWavelength 6563.0

HbetaWavelength 4861.0

HgammaWavelength 4340.0

HdeltaWavelength 4101.0

HepsilonWavelength 3968.0

He2Wavelength 4686.0

This determines whether or not you calculate the extinction coefficient c.

It should be set to "on" unless you are using data that has already been

extinction corrected. It will cause the program to exit if the

BalmerDecrement is "on" and it is not.

DereddenData on

```
# These control the expected ratio of H-alpha or H-gamma to H-beta. They are
# used for calculating the extinction coefficient. It is both temperature
# and density dependent and may be calculated or set to a constant value.
# To calculate this value set BalmerDecrement to "on" while DereddenData is
# "on" as well.

HalphaHbetaRatio 2.86
HgammaHbetaRatio 0.469
BalmerDecrement on
BalmerToggle alpha

# This specifies whether or not you want to automatically deblend *'ed lines
# in your SpecFile using the routines from elsa_deblend.c to do activate set
# DeblendLines to "on".

DeblendLines on

    # This specifies the maximum number of lines that can be read from
# a data file (IRAF or abun format) and the maximum number of
# reference wavelengths that can be read from a spec file. The higher
# you set it, the more memory PNe will allocate, so set it to whatever
# you feel that you need.
```

MaxLines 512

MaxSpec 512

EGStellarAbsorption off

E. A Portion of the Default Wavelength Specification File, "wavelengths.txt"

3727 [O II]

3770 He II + H11

3797 He II + H10

3835 He II + H9

3868.75 [Ne III]

3889 He I + H8

* 3968 [Ne III] + H-epsilon

4008 He I + [Fe III]

4026 He I + He II

4046.40 [Fe III]

4071 [S II]

* 4101 H-delta + He II

4120.84 He I

4143.76 He I

4166.95 C III

4199.83 He II

4227.20 [Fe V]

4267.00 C II

* 4340.47 H-gamma

4363.23 [O III]

F. Custom-Created File for ELSA

3726.176 0 9.807E-13

3751.799 0 1.344E-13

3769.850 0 1.351E-13

3797.089 0 2.417E-13

3834.220 0 3.374E-13

3867.354 0 5.189E-12

3887.247 0 9.736E-13

3966.448 0 2.338E-12

4024.474 0 1.122E-13

4067.908 0 7.514E-14

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