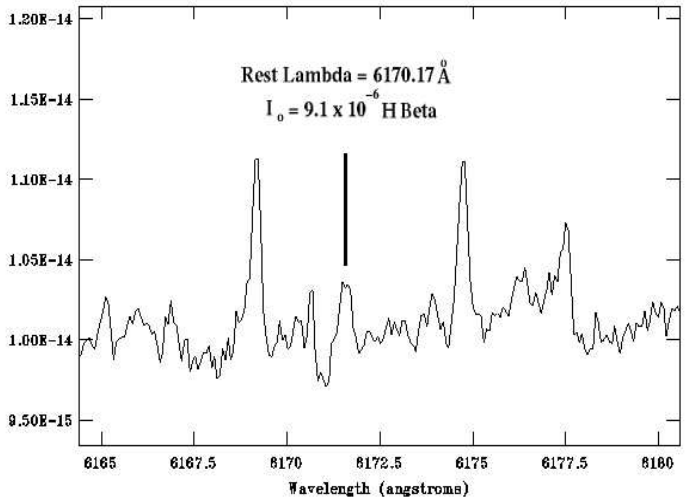
EMILI - An Aid to Emission Line Identification In Emission-Line Regions




```
Observed Line:   6170.17  9.1E-06  S/N:     8.70 FWHM:   15.5
   6170.13 |     6169.668  Ar II      1209158728     265  1.1E-05  22.7 6/0 9
   6170.17 |     6169.720  Fe III     1747355991     262  1.1E-04  21.9 5/0 8
   6170.17 |     6169.740  Fe III     1747354965     262  1.1E-04  21.0 2/0 8
   6170.13 |     6169.830  Si III      941708340     262  2.2E-04  14.8 0/0 6D
   6170.09 |     6169.798  Fe I       1745385607       8  4.2E-05  14.0 2/0 8
   6170.13 |     6169.903$ Ne I        671136779     648  1.2E-04  11.3 0/0 6D
   6170.17 |     6170.000  Mg VII      811641895     259  2.1E-06   8.3 2/0 9
   6170.17 |     6170.000  Ne VII      677436466     259  6.5E-06   8.3 0/0 6D
   6170.09 |     6169.916  Fe I]      1745168490      24  1.3E-06   8.3 */0 9
+  6170.09 |     6170.034  Si I        939713550     263  3.1E-05   2.5 0/0 4C
+  6170.13 |     6170.160  N  II       470858782     262  3.5E-04  -1.3 5/2 1A 6167.750  -5.1 6173.310  -0.8
+  6170.13 |     6170.174$ Ar I       1208044554       8  3.6E-06  -1.9 0/0 3B
   6170.13 |     6170.260  Mn III     1680218462       6  1.3E-06  -6.1 8/0 8
   6170.13 |     6170.280  Fe II      1746413872       6  1.7E-04  -7.1 4/0 6D
   6170.09 |     6170.280$ Si I        939952150       6  2.8E-05  -9.4 0/0 6D
   6170.08 |     6170.400  Ca I       1342907756       5  7.4E-07 -15.5 0/0 8
   6170.09 |     6170.506  Fe I       1745302650       8  4.8E-05 -20.4 4/0 8
   6170.13 |     6170.620$ Ni II      1880779025       6  5.9E-06 -23.6 0/0 7
   6170.17 | >   6170.692  He II       135432222       7  6.3E-04 -25.3 0/0 0<
```

Manual for Version 4 - January 9, 2003

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Contents

1. Introduction and Purpose

The **EMILI** code is designed to aid in the identification of weak emission lines, particularly those weak recombination lines seen in high dispersion, signal to noise spectra. The program utilizes a three facet approach to obtain this goal. First, we derive maximum utility from a large atomic transition database: Atomic Line List v2.04 (van Hoof 2001). Even for those transitions which lack values for atomic parameters, we can make rough estimates of line strengths, so that every transition can be considered as a possible ID for some observed line. Thus, many more transitions can be utilized here than could be considered manually, or that could be included in emission spectra models which rely on precise knowledge of such atomic parameters. Secondly, the code carries out time-consuming checks, which are usually done manually, such as searches for other multiplet lines, in a rapid and automated fashion free from observer bias. Finally, the program provides an easily understood ranking criteria to allow the user to readily chose among potential IDs.

The code is not meant to model the emission spectra of its target objects, but rather to aid in the identification of weak lines by providing many alternative IDs and by informing the user of the results of simple tests that can strengthen or weaken each IDs' case. It is an efficient, automated version of the sort of traditional line identification methods done manually for decades.

The code is written entirely in FORTRAN 77, for ease of interpretation by other users (maybe I speak too soon before you get a chance to actually LOOK at the code!). This distribution (number 4) contains all of the subroutines, default data files, and sample input and output, in a single zipped file. Please see § 3 for the installation and operation of the code.

This document is intended as a user's manual for the code. A comprehensive review of the logic behind the code itself can be found in Sharpee et al. (2003).

IMPORTANT: Please make sure you are using the most recent edition of the code:

`http://www.pa.msu.edu/astro/software/emili/`

has the most up-to-date and tested version.

2. User Inputs

EMILI recognizes the following user inputs, some of which are required and others optional, depending upon what facilities of the program the user wishes to utilize.

Required: *Input Line List*

Optional: *Matched Line List*,
Abundance Table

In addition a *Command/Parameter List* is also required to set certain parameters used by the code as well as the names of input/output files.

2.1. Input Line List

This is a list of unidentified lines that the user wants to identify. These lines must have observed wavelengths between 3000-11000Å, the range of a typical optical echelle spectrum. The user specifies the observed wavelength in Å, the measurement/systemic error on either side of the observed value, also in Å, the flux of the line with respect to Hβ, the FWHM in km/s, and the signal-to-noise of the line. Currently the final two parameters, FWHM and signal to noise, are not employed directly by the **EMILI** code, and are simply propagated into the output to give the user full knowledge of each line the code identifies. Placeholder numeric values can be employed for these parameters.

Users submit a line list in the form of an ASCII text table, with the information specified above for each particular unidentified line comprising an individual line in the table, ended with a carriage return. Information is read in FORTRAN free format, with blank space separating each individual element on the line. Each element in the line is a FORTRAN "REAL" variable. The code currently accepts up to 1500 unidentified lines. No blank lines should be left at the end of the table, and no special indicators need be included to signify the end of the file. The *Input Line List* is read in by a statement in the main routine: **em4.f**. An example of a segment of an *Input Line List* is given in Figure 1 (from the file **ic418.in** included with the distribution).

2.2. Matched Line List

This list includes manual identifications made for some of the unidentified lines in the *Input Line List*, usually for strong lines where the identifications are unambiguous. The user specifies the observed wavelength (in Å), the laboratory wavelength of the transition he or she believes is responsible for the line (also in Å), the ion responsible for the transition in spectroscopic notation, and the observed flux in the line with respect to Hβ. **EMILI** can use this information in two ways:

1. *Velocity Structure Correction:* All the ions from elements $Z \leq 30$, are grouped together into five "bins" determined by ionization energy. The energy bounds of these bins are described in Table 1. For each manual identification in the *Matched Line List* the velocity difference between the observed and laboratory transition is credited to the bin in which the source ion belongs. Recombination lines here are assumed to originate from the ion of the next higher ionization state than that given in the spectroscopic notation, while collisionally excited and a few intercombination lines (those going to near-ground energy levels) are assumed to originate from the ionization state indicated by the notation. The average is then taken for each bin to establish a correction to be applied to the wavelength of each observed line appropriate for the ion responsible for a transition being tested as a possible match to that line. Thus the systemic velocity and any ionization energy dependence of the expansion velocity of the object can be accounted for, if not already done so beforehand in the data. Alternatively, this feature may be turned off, or manual values for the correction in each bin can be specified in the *Command/Parameter List.* The calculated or submitted values will be listed in the *Full Output List* (see § 5.1).

2. *Ionic Abundances:* To establish ionic abundances for all ions $Z \leq 30$ the presence of certain "signature" lines (see Table 2) is sought in the *Matched Line List.* The relative strengths of these lines with respect to Hβ, if present in the spectra and recorded in this list, are used to establish ionization correction function (ICF) values for each energy bin. These are roughly percentages that particular ions of that element take up of the entire abundance for that element. Depending upon the bin in which a particular ion resides, as well as the one in which the ion from the same element with the next lower stage of ionization can be found, ionic abundances are calculated. If the ion and the next lower stage ion have ionization potentials which reside in the same bin, the ICF value for that bin is multiplied by the abundance for the overall element listed in the *Abundance Table.* If they reside in different bins then the average of the ICF values from each appropriate bin is utilized to obtain an ionic abundance through multiplication again with the overall elemental abundance. Exceptions to these rules include the ionic abundance for ionized hydrogen, which is defined as the second bin ICF value times the hydrogen abundance, and the ionic abundances for first and completely ionized helium, which are defined as the are the overall helium abundance multiplied by the third and fourth ICF bin values respectively. If some of the signature lines are not present in the spectra or not recorded in the *Matched Line List* because their identification manually is ambiguous, the code will attempt to make reasonable guesses as to the ICF values from those lines that are present. Alternatively, the program can use a default set of reasonable ICF, or a manually chosen set, as specified in the *Command/Parameter*

List. The calculated or default values will be recorded in the *Full Output List*.

While the *Matched Line List* is optional, it must be present to utilize the ICF value and velocity correction calculation routines, present in **EMILI** . If a *Matched Line List* is not used, one must specify the ICF and velocity correction parameters for each energy bin either manually, or use the default values, in the *Command/Parameter List*.

If included, the *Matched Line List* must take the form of an ASCII table, with the information about each specified line comprising one line of the table, individual values separated by blank space, and ended by a carriage return. While read in with the FORTRAN free format the information on each matched line comprising a line in the list must satisfy the following convention in the following order:

- observed wavelength: A FORTRAN "REAL" variable, read in free format.
- laboratory wavelength: Also a FORTRAN "REAL" variable, read in free format.
- the element notation: This is a three place character variable: FORTRAN "CHARACTER*3". If the line is a forbidden line, the first character must include the "`[`" symbol. Non-forbidden lines or intercombination lines must start with the elemental notation. If the notation doesn't reach three characters the remaining space should be filled with *blank* spaces.
- a single *blank* space between arguments.
- the ion notation: This is six place character variable: FORTRAN "CHARACTER*6". The particular ion must be specified in Roman numeral format, with the standard astronomical convention (i.e. Na I is neutral sodium, Na II is first ionized sodium etc...). If the line is an intercombination of forbidden line, the next character immediately after the end of the Roman numeral specification must be the "`]`" character. If the entire information comprises less than six characters, *blank* spaces should be used to fill out the remaining places.
- the flux with respect to Hβ: A FORTRAN "REAL" variable, read in free format.

Users are limited to 50 matched lines in total. A line headed by a "`Z`" in it's first character will be ignored by the code and does not count in the total number of matched lines that can be specified. No blank lines should exist in the file, and no special end of file indicators are necessary. The *Matched Line List* is read in by a statement in the subroutine: **matchlist4.f**. An example of a *Matched Line List* is given in Figure 2 (from the file **ic418.match** included with the distribution).

2.3. Abundance Table

EMILI comes with a default abundance table: **abun.dat**, which are solar abundance values for each element $Z \leq 30$ with respect to hydrogen. One may specify an alternative abundance table in the *Command/Parameter List*. Values need not be with respect to hydrogen in a user supplied table, however in that case the numeric absolute abundance of hydrogen must be specified. This is necessary in order to normalize the other elemental abundances, to the values used by the code to calculate the *Template flux* (see § 4). **EMILI** will query you if a possible line ID does not have a matching abundance for its source ion.

If an abundance table is specified, it must be in the format of an ASCII table, where information about individual elements must be placed on an individual line in the that table, one element per line. As usual, blank spaces must separate the information on each line, and each line must be ended by a carriage return. While read in by FORTRAN free format, each line must follow a certain convention. The element, listed in standard notation, is a FORTRAN "CHARACTER*2" variable, followed by a blank space, followed by the value of the numeric abundance (read in as a free format FORTRAN "REAL" variable). Again, no end of file indicator is necessary, and the file must not include blank lines. The user must use elements which are only $Z \leq 30$. The code currently can't accept additional elements, and the transition database only has information for $Z \leq 30$ elements.

The abundance table is read into the program from a statement in the subroutine: **matchlist4.f**. For an example of a properly formatted *Abundance Table*, see: **abun.dat**, included with the distribution.

2.4. Command/Parameter List

Here is where **EMILI** receives additional information it will utilize in its calculations. This information is generally broken into two classes: input and output file names, and parameter specifications. Some of these parameters are required and some are optional. A sample command list: **ic418.cmd** is included with the distribution and diagrammed in Figure 3.

The command list is a simple ASCII text table, with each line setting a file name or parameter. Each line in the list consists of a command (`A,L,M,I,O,D,T,N,deplete,vel,icf`) followed by various arguments. Each line may be no more than 60 characters in length, with individual arguments no longer than 15 characters, ended with a carriage return, one command per line. There may be up to 5 arguments depending upon the command. Commands may be placed in any order. A "`Z`" placed in the first column of any line will cause

the code to skip that line. **EMILI** will warn if certain commands are repeated or if they conflict, before run time. The list is read in by a statement in the subroutine: **openall4.f**. A detailed description of each line in the included list (Figure 3), which lists every possible command perturbation, is given below.

Required:

- "`L ic418.in`" This specifies the name of the file for the *Input Line List.*
- "`T 10000`" This sets the electron temperature to 10000 K. This is utilized in the calculation of *Template Flux* values.
- "`N 10000`" This sets the electron density to 10000 electrons/cm^3. This is also utilized in *Template Flux* calculations.
- "`I 10`" This sets the instrumental resolution or natural line width, whichever is the largest, to 10 km/sec. This is utilized by the *Multiplet Check*, to determine if certain multiplet lines are too close to be fully resolved, and thus not searched for during that phase of the code's calculations.
- "`vel+`" Commands starting with "`vel`" indicate how the velocity structure should be calculated. The calculation may be carried out in three different ways, reflected in these three options:
  - "`vel+`" Calculate the velocity correction for each energy bin (see Table 1) from the data of the *Matched Line List.* In order to use this option you must specify the file name for the *Matched Line List* in this *Command/Parameter List.*
  - `vel-`: Assume that the observed lines already have been corrected to the nebular rest frame, and that there is no ionization energy dependent velocity flow. This essentially sets the velocity correction value to zero for each energy bin.
  - "`vel 99 99 99 89 89`" Use the values specified as arguments as the velocity correction values (in km/sec) to apply to an ion residing in each of the five bins.
- "`icf+`" Commands beginning with "`icf`" specify how the ICF values for each bin should be specified and consequently used to calculate ionic abundances. These calculations may be performed in three different ways, specified here by three different formats:
  - "`icf+`" Calculate the ICF values for each bin from the data of the *Matched Line List.* If this option is used a *Matched Line List* must be specified in this *Command/Parameter List.*
  - "`icf-`" Use the default ICF values for each bin (see Table 2).
  - "`icf 0.1 0.2 0.3 0.3 0.1`" Use the values specified as arguments as the ICF values to be applied to ions in each of the five energy bins. These must sum to one.

Optional:

- "`M ic418.match`" This specifies the name of the *Matched Line List*. If this command is not included, one must choose to use manual or default values for the velocity correction and ICF values for each bin.
- "`O ic418.out`" This specifies the name of the file to include the *Full Output List*. If the command is not included, an ".out" will be tacked onto the *Input Line List* name and used as the file name.
- "`D ic418.dat`" This specifies the name of the *Summary List*. If this command is not included, a ".dat" will be tacked onto the *Input Line List* name and used as the file name.
- "`A abun.dat`" This specifies the name for the *Abundance Table*. If not present in the *Command/Parameter List* the code will utilize the default table: **abun.dat**.
- "`deplete Fe 50 1 2`"

  Lines beginning with "`deplete`" tell **EMILI** to reduce the abundance of certain ions, after the ionic abundances have been calculated using the ICF values. This command may have up to four arguments specified in the following order:

  1. The element to deplete.
  2. The amount to deplete (negative values enhance).
  3. The lower end of the range of ionization states to deplete.
  4. The upper end of the range of ionization states to deplete.

  The following examples illustrate the options that **EMILI** will assume if specific arguments are missing:

  – "`deplete Fe 50 1 2`" No arguments are missing. This example would ask **EMILI** to deplete the abundances of Fe I and Fe II by a factor of fifty.

  – "`deplete Fe 50 1`" Argument four is not present in the command. **EMILI** will assume that only the ion indicated by argument three will be depleted. Thus in this example only Fe I would be depleted by a factor of fifty.

  – "`deplete Fe 50`" Both arguments three and four are missing. **EMILI** will deplete all the ions of the indicated element. In this example all the ions of iron are depleted by a factor of fifty.

  Arguments one and two must be present for a valid command.

3. Installing and Running the Code

1. One should un-compress and un-archive the file: **em4.tar.gz** into an empty directory. All of the subroutines and data files will be placed in that directory after un-archiving. No additional sub-directories are created. Follow these commands:

```
>cd (name of the directory in which to place \emili)
>gunzip em4.tar.gz
>tar -xvf em4.tar
```

2. In that directory, compile the code by executing the make file: **./em4.mak**. This is included as part of the distribution.

```
>./em4.mak
```

   The code should compile and run, although in differing Unix platforms the various compilers may complain. On my Red Hat distribution with the generic "f77" compiler, I receive no complaints. The make file assumes that a "f77" compiler exists on your machine.

3. Run the code from the command line:

```
>./em4 cmdlist
```

   where **cmdlist** is the name of the file containing the *Command/Parameter List*.

One should now see various things, starting with a welcome message, followed by a check of the *Command/Parameter List* for errors and proper format. If all is well, the program will echo to the screen the parameters you have entered, wait for a carriage return, then read in the transition and level information databases, before executing. If there are any "fatal" errors in the *Command/Parameter List*, you will need to correct them before the program will run. Don't be alarmed if it takes a while to read in the transition database, as it includes 280,000 transitions in the specified optical range. EMILI will describe what it is doing every step of the way.

You will know the program is working on the data the user provided when long "block" lists of information begin scrolling on your screen, one for each line in your *Input Line List*.

The screen output is echoed into the *Full Output List* (see § 5.1) along with the ICF and velocity correction values, either specified in the *Command/Parameter List* or calculated by the code, as well as the other parameters specified in the *Command/Parameter List*.

When completed the program will drop you back to the shell, where you can look at the *Outputs* (see § 5) in your favorite text editor.

Try it with the included command/parameter and line lists: **ic418.cmd**, **ic418.match**, and **ic418.in**:

```
>./em4 ic418.cmd
```

Yields:

Full Output List:	**ic418.out**
Summary List:	**ic418.dat**

On my 700 MHz notebook it takes about 5-6 minutes to process the 805 lines in the list: **ic418.in**.

4. The EMILI Process

The process begins by reading in the information about each unidentified line the user wishes to have **EMILI** identify from the *Input Line List*. If the user supplies a *Matched Line List*, and if the appropriate commands have been issued in the *Command/Parameter List*, the code will use the pre-identified lines to make *Ionic Abundance* calculations, and to determine if any *Velocity Structure* may be present, calculating any necessary correction values. If the *Matched Line List* is not supplied, or if the ICF value and velocity structure commands have been set not to use the *Matched Line List*, the same calculations will be carried out with the default or manually specified values.

For each unidentified line, the code searches the transition database for all lines within 200 km/sec, to account for the largest possible systemic velocity for nearby emission-line regions. These comprise the first set of putative IDs for that line. The *Velocity Structure Correction* (manually specified or computed by the code), appropriate to each putative ID's source ion, is then applied to the observed wavelength of the line being identified in order to bring the observed value into the nebular "rest frame" for the region where that ion resides. Further consideration is given only those putative IDs for which the residual wavelength difference after correction is less than (currently) five sigma of the observed value's measurement error (transition wavelength uncertainties are currently **not** included

in the error). For each surviving putative transition a *Template Flux* with respect to Hβ is calculated, which is a predicted, order-of-magnitude estimate of the strength of that line, under the specified nebular conditions (temperature and density supplied by the user). This estimate is based on makes several simplifying assumptions about each transition:

1. Each transition has both a collisionally excited and recombination component to its strength.

2. The collisionally excited portion of the flux uses order of magnitude estimates of collision strengths and transition probabilities according to the type of transition (electric dipole, magnetic dipole, electric quadrupole) it represents. The collisional component assumes a simple two level atom, and allows for collisional de-excitation.

3. The recombination excited portion also uses a generic spontaneous transition coefficient, and is considered insensitive to either temperature or density, being influenced mostly by the direct abundance of the source ion. It also assumes a two level atom and does not employ any branching ratios.

Only transitions which are within a factor of 10^3 of the highest calculated template flux among all putative IDs considered at this stage are retained. This assumes that the transitions predicted to be the strongest are the most likely to actually manifest themselves in the spectrum as an observed line.

Upon these remaining putative transitions a *Multiplet Check* is carried out. This involves looking for companion multiplet lines in the *Input Line List*, of the same or stronger transition type, which are approximately close both in wavelengths and expected observed flux. It is expected that the ratio of the products of the statistical weights and Einstein coefficients between the putative ID transition and another transition from the same multiplet, should be fairly close to the ratio of their associated lines' observed flux ratio, within a factor of three. If the Einstein coefficients are not available for these transitions, or if comparing different types of transitions (such as magnetic dipole versus electric quadrupole) the code assumes that the ratio of observed fluxes should at least be within a factor of ten (or 10^{-4} when a weaker-type transition type is compared to a stronger type). Since multiplet lines arise from the same element and creation mechanism, they should also show the same residual velocity differences between corrected observed values and laboratory wavelengths. This check is **only** carried out for lines originating from pure LS coupling levels.

Finally, the code uses the residual wavelength difference between the corrected wavelength of observed line and the putative ID's laboratory transition, the relative strength of

its *Template Flux* with respect to other putative IDs surviving to this stage, and the results of the *Multiplet Check* to rank the potential IDs. This is done by assigning a numeric Identification Index (*IDI*) value, derived from these criteria, to each putative ID. See Table 3 for a detailed explanation of how this score is calculated.

5. Outputs

EMILI generates two output files, whose names the user may specify in the *Command/Parameter List*:

Outputs: *Full Output List,*
Summary List

We describe the *Full Output List*, and *Individual Line Identification* within that list, and *Summary List* in the following sections.

5.1. Full Output List

The distribution comes with a sample *Full Output List*: **ic418.out**, which will be regenerated if the code is run with an unaltered command list: **ic418.cmd**. The output consists of five parts (the first four depicted in Figure 4) listed in the following order:

1. *Parameter Summary:* This will echo those parameters specified in the *Command/Parameter List*, including file names, electron temperature or density, and the instrumental resolution/natural line width.

2. *ICF Values:* The value for each ionization energy bin is listed here.

3. *Elements Depleted:* The ions that were depleted or enhanced in the *Command/Parameter List*, and the amount by which they were depleted or enhanced.

4. *Velocity Structure:* The velocity correction in km/sec applied for all ions residing in each energy bin.

5. *Individual Line Identifications:* There then follows several "blocks" of information. The output contains one such block of information for each unidentified line in the *Input Line List*. This block includes an individual line's potential identifications (up

to 100 per each line), derived from the results of the checks carried out by the code. Following the first row, which reiterates the observed parameters of the line, each succeeding row lists a "putative" ID, drawn from the transition database, that the code has judged to be a possible ID. Each transition is listed in order of velocity residual between the corrected observed wavelength and the laboratory wavelength of the putative ID, starting with the greatest value to one side of the corrected observed wavelength, proceeding to the greatest value on the other side. An example of an identification of a line observed at 6347.19Å after correction to the nebular rest frame, from the included *Full Output List* **ic418.out** is given in Figure 5. We detail the format of this figure in the following section.

5.2. Sample Line Identification

Format of a sample *Individual Line Identification* from the *Full Output List* (see Figure 5):

The first row contains the observed parameters of the particular line, including observed wavelength, flux with respect to Hβ, signal to noise, and FWHM in km/sec, drawn from the *Input Line List*. There then follows a table of information, whose columns provide the following information:

Columns:

- **A.** The observed line's wavelength corrected appropriately for the ion responsible for the putative ID transition in that row. A plus before the value indicates that the transition's laboratory wavelength and the corrected observed wavelength are less than one sigma of the observed value's measurement error apart.

- **B.** The putative ID's laboratory wavelength. A "$" following the wavelength value indicates that the transition involves a non LS coupling level as either or both the origin and destination level. As mentioned, the *Multiplet Check* is not currently carried out for such putative IDs. An "*" following the wavelength value indicates that all of the multiplet lines involving the particular putative ID, are unresolvable because they are all within the natural line width or instrumental resolution specified in the *Command/Parameter List*. These are collapsed into a statistically weighted single line of the wavelength proceeding the "*". The *Multiplet Check* is not carried out for these lines. The code is currently limited to collapsing lines down if all of the multiplet lines are within the instrumental resolution/natural line width. Thus, if two of six lines of

a particular multiplet, could be blended, the code considers each of those two as a separate ID. This will be a focus of continuing work in the next version of the code.

- **C.** The spectroscopic notation for the putative ID.
- **D.** An internal reference number for this transition in the Atomic Line List v2.04. This integer, along with the integer in column **E**, can be used with an auxiliary reader included with the **EMILI** distribution (see § 5.4) to obtain information about the electronic configuration, term notation, and angular momentum j values belonging to the levels this transition traverses.
- **E.** A second internal reference number for the transition.
- **F.** The *Template Flux* calculated for the putative ID.
- **G.** The residual wavelength difference, measured in km/sec, between the corrected observed value of the line, and the laboratory wavelength of the putative ID.
- **H.** The *Multiplet Check* statistics, with the numbers of expected multiplet lines, followed after the slash by the number of lines found to have potential matches in the *Input Line List*, not including the putative line itself.
- **I.** The **EMILI** assigned **IDI** value (see Table 3) which serves as a measure of the "goodness" of the match based upon the criteria mentioned above, with lower numbers indicating better IDs. **EMILI** also assigns a letter "A,B,C, or D" to indicate primary, secondary, tertiary, and fourth ranked identifications, based upon the relative numeric scores.
- **J.** Here is where supporting results from the *Multiplet Check* are noted. Additional multiplet lines' laboratory wavelengths that were found to correspond with other lines in the *Input Line List* are listed here along with the residual velocity difference with those observed lines, for comparison with the same value in column **E**. Up to three lines, if they can be found, will be displayed here, listed in order of decreasing observed strength.

In the final row of each individual line identification, beginning with a "**>**" and ending with a "**<**", in the location where a rank would go in the column **I**, is listed the transition with the strongest calculated *Template Flux* in the anulus between the initial **EMILI** acceptance radius and twice that radius away from the observed wavelength. As mentioned, **EMILI** is currently set to accept only those transitions within 5σ of the observed wavelength for template flux calculations, where σ is the measurement uncertainty of the line being ID'd.

Thus, this row includes the predicted strongest template flux transition in the region 5 – 10σ away from the wavelength for that line in the *Input Line List*. The putative ID has no bearing on the rank of the other putative IDs (no *IDI* score is assigned), but the multiplet check is carried out. This was primarily put in to handle occurrences where the transition's laboratory wavelength in the database appears to be highly suspect (such as is the case for [Ne III] λ3868Å), and to allow them to be considered as additional alternative IDs.

5.3. Summary List

This file contains a summary of the **EMILI** results (see Figure 6 and the included file **ic418.dat**). For each unidentified line subjected to testing by the code, the corresponding primary ID or IDs, indicated by an "`A`" in column **G** in the *Full Output List* along with their laboratory wavelengths, are listed adjacent to that line's measured attributes (observed wavelength and flux with respect to Hβ).

5.4. Reader

A separate program is included with the distribution which reads the **EMILI** output and provides more detailed information regarding the transitions the user may choose as IDs then collating the information in an additional output file. Specifically, this reader will take a **EMILI** *Full Output List*, marked-up according to a simple scheme, and extract the information for user-chosen putative IDs, using the previously mentioned internal reference numbers found in the output, then tabulate it in a `ASCII` text file. These internal reference numbers provide information regarding the transition's atomic parameters and type. This allows for more rapid **EMILI** derived identifications, without generating gigantic lists of such information in the actual **EMILI** output files during run-time.

To use the reader, the user simply marks on the **EMILI** *Full Output List* an "`*`" in the first space of the any row containing a putative ID of interest. This may be done for as many lines and for as many putative IDs for those lines as the user wishes. Entries will be generated in a user-named file. The routine will reference the transition database and provide information about these transitions in the same file.

For instance, suppose I were to mark an "`*`" in the first space of the row containing the putative ID that begins with:

```
*+  6347.15 |    6347.110  Si II      940585992    262  ...
```

The reader would generate a corresponding entry in the reader output file:

```
*+ 6347.19  47.7 5.1e-4  83.3 2A Si II 6347.11 2S 3s2.(1S).4s 2Po 3s2.(1S).4p ...
```

where from left to right are observed wavelength, FWHM, flux, and S/N (as supplied in the *Input Line List*), then the ion, accepted rest (laboratory) wavelength, the upper and lower energy level terms and electron configurations, and finally the upper and lower total angular momentum j values for the levels traversed by the particular putative ID transition (entry is truncated here for space reasons). If additional IDs are marked for the same emission lines, these will align in the output file with the transition information for the first ID that the reader encounters in the individual line output lists.

To invoke the reader simply compile at the command prompt:

```
>./emread.mak
```

then run at the command prompt:

```
>./emread arg1 arg2
```

where "`arg1`" is the name of the marked-up **EMILI** *Full Output List* and "`arg2`" is name chosen by the user for the results file.

6. Future Improvements

In future editions of the code, we plan on making three major improvements.

1. Broader Line List: A still larger and more comprehensive transition database is currently being constructed (Atomic Line List v2.05), which will expand the transition list to include all elements $Z \leq 36$ (up to all fourth row elements), and will include improved Coulomb calculations of transition probabilities.

2. Cross Correlation: Presently the code does not seek corroborating information about a particular putative ID, from the putative IDs of other unidentified lines, beyond those comparisons made during the *Multiplet Check*. Future editions of the code will compare the expected line strength ratio between different lines of differing multiplets with the observed value, and compare the velocity residuals between putative IDs of the same ion and creation mechanism.

3. Multiple Iterations: We plan on making the code iterative, using the best IDs from an initial run to re-calculate and improve the accuracy the ionic abundances and velocity structure corrections, for use in successive runs.

We will also be attempting to optimize the weighting given to each component (residual wavelength difference, relative template flux, and multiplet check results) used to construct the final score and subsequent rank for each putative ID for a particular unidentified line. This in order to ascribe more importance to those components which might be more or less appropriate for differing observing parameters (i.e. less emphasis on the residual wavelength difference for lower dispersion spectra etc.).

7. Contact Information

This code is always evolving, and as such is still undergoing testing and revision as I write this, so please pardon the dust (a.k.a. numerous test comments scattered throughout its length). I cannot guarantee that the code is entirely "bug-free" yet (*caveat emptor*). However I hope you are able to use the code with as little trouble as possible, and that it provides you with interesting and accurate results. I am most happy to answer any questions and would appreciate reports of any errors you believe the code is making. Suggested improvements are always welcome.

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For further details and updates please stop by the **EMILI** web page at:

`http://www.pa.msu.edu/astro/software/emili/`

REFERENCES

Sharpee, B., Williams, R., Baldwin, J.A., & van Hoof, P.A.M., 2003, ApJS, accepted (astro-ph/0307053)

van Hoof, P.A.M., Atomic Line List v2.04, 2001, http://www.pa.uky.edu/∼peter/atomic

This preprint was prepared with the AAS LaTeX macros v5.0.

Table 1: The ionization energy bins used to determine ICF values and velocity corrections to the observed line as a function of putative ID ion's ionization energy.

Bin	Ionization Energy (ev)
1	0-13.6
2	13.6-24.7
3	24.7-54.5
4	54.5-100.0
5	> 100

Table 2: The lines specifically used to calculate the ICF values, and their defaults in each bin.

Bin	Energy Range (ev)	Default Value	Signature Lines
1	0-13.6	0.01	Mg I] λ4571, Na I $\lambda\lambda$5890, 5896, [S I] λ7775, [C I] λ8727, Ca II (H&K) $\lambda\lambda$3934, 3968
2	13.6-24.7	0.3	He I $\lambda\lambda$5876, 4471
3	24.7-54.5	0.3	He I λ5876, 4471
4	54.5-100.0	0.2	He II λ4686
5	> 100	0.1	[Fe X] λ6375, [Ne V] λ3426, [Fe VII] λ6087, [Ar X] λ5533

Table 3: For each observed unidentified line, all putative IDs are ranked, by defining a "score" or IDI value for each transition. The IDI is awarded on the basis of the putative ID meeting the main criteria listed below. A lower score generally means a better ID.

1. Flux Basis (F)

Putative ID template flux satisfies the following condition:

F	Condition
0	Exceeds computed fluxes of all other putative IDs by factor ≥ 10.
1	Within a factor of 10 of the largest putative ID template flux.
2	Within a factor of 100 of the largest putative ID template flux.
3	Within a factor of 1000 of the largest putative ID template flux.

2. Wavelength Basis (W)

The residual wavelength difference (in km/s) between the corrected observed line's wavelength and that for the putative ID is within a number of measurements sigmas (σ) of the observed line's corrected value:

W	Conditions
0	$\leq 0.5\sigma$
1	$\leq 1.0\sigma$
2	$\leq 1.5\sigma$
3	$\leq 2.0\sigma^{(a)}$

(a) code currently set to include only transitions $\sigma \leq 2$

3. Multiplet Basis (M)

For a putative ID, detected multiplet members, D, and possibly observable members, P, satisfy:

M	Conditions
0	$P/D = 1/1\,, D > 2$
1	$P/D = 0/0\,, 2/1$
2	$P/D = 1/0\,, (> 2/1)$
3	$P/D = (> 1)/0$

$$\text{IDI} = F + W + M, \text{ with equal weight to each factor.}$$

A	B	C	D	E	F
6363.89	-0.08	0.08	7.58e-03	56.70	485.20
6371.42	-0.08	0.08	4.33e-04	31.00	198.30
6379.65	-0.11	0.11	8.62e-06	25.50	10.70
6382.99	-0.11	0.11	1.95e-05	44.10	16.10
6392.50	-0.11	0.11	9.28e-06	17.60	6.20
6402.27	-0.08	0.08	1.07e-04	21.90	75.50
6454.39	-0.11	0.11	1.01e-05	22.40	5.40
6456.00	-0.11	0.11	1.25e-05	19.30	8.70
6461.85	-0.08	0.08	5.83e-04	18.60	93.50
6527.26	-0.08	0.08	2.84e-04	29.30	70.60
6548.10	-0.08	0.08	5.35e-01	39.80	10430.00
6562.80	-0.08	0.08	3.12e+00	31.30	14100.00
6578.05	-0.08	0.08	5.37e-03	18.30	870.50
6583.47	-0.08	0.08	1.63e+00	40.20	11370.00
6610.65	-0.11	0.11	2.79e-05	25.00	11.70

Fig. 1.— A subset of the *Input Line List* from **ic418.in**. Listed in columns from left to right are: **A.** observed wavelength (Å) **B.,C.** errors in measurement (Å), **D.** flux with respect to Hβ **E.** FWHM (km/sec) **F.** signal to noise.

5006.845	5006.843	[O	III]	2.15e+00
6583.467	6583.450	[N	II]	1.63e+00
3726.035	3726.032	[O	II]	1.24e+00
4958.915	4958.911	[O	III]	7.27e-01
6548.088	6548.050	[N	II]	5.36e-01
3728.785	3728.815	[O	II]	5.23e-01
9530.929	9530.600	[S	III]	4.23e-01
9068.905	9068.600	[S	III]	1.78e-01
7319.087	7318.920	[O	II]	3.69e-02
7320.135	7319.990	[O	II]	1.01e-01
7329.679	7329.66	[O	II]	5.86e-02
7330.754	7330.73	[O	II]	5.63e-02
5875.650	5875.640	He	I	1.37e-01
7135.744	7135.773	[Ar	III]	8.26e-02
4471.499	4471.486	He	I	4.49e-02
6730.893	6730.816	[S	II]	4.42e-02
6678.153	6678.152	He	I	3.87e-02
3868.745	3868.750	[Ne	III]	3.09e-02
A	**B**	**C**		**D**

Fig. 2.— A *Matched Line List* (**ic418.match**). Listed in columns from left to right are: **A.** observed wavelength (Å) **B.** laboratory wavelength of transition (Å), **C.** spectroscopic notation for the transition's source ion **D.** flux with respect to Hβ

```
A abun.dat
M ic418.match
O ic418.out
D ic418.dat
T 10000
N 10000
I 10
L ic418.in
vel+
icf+
Z deplete Fe 50 1 2
```

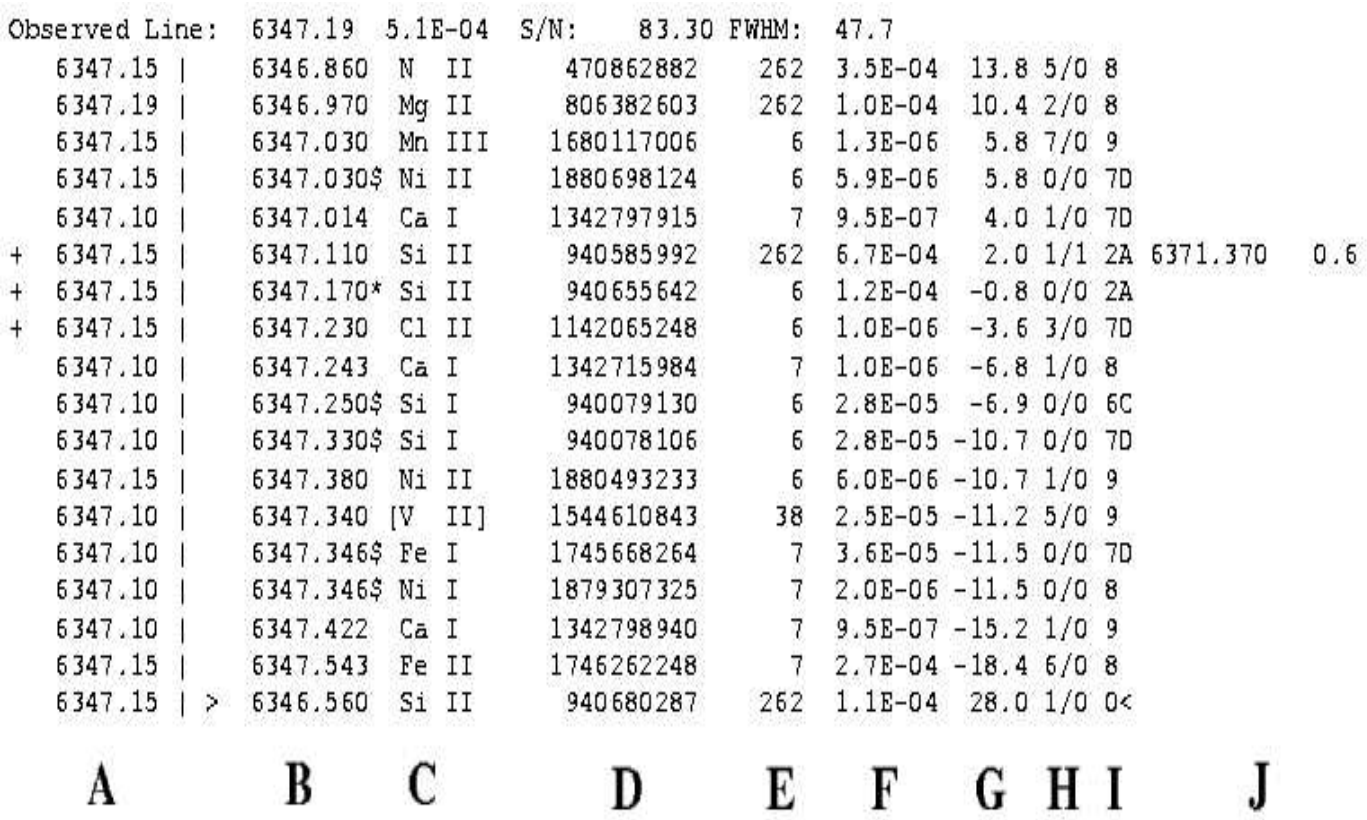
Fig. 3.— A *Command/Parameter List* (**ic418.cmd**).

```
EMILI Output File
-----------------------------------
Input Line List: emili8.in
Input Matched List: emili8.match
Results List: emili9.out
Short Results List: emili9.dat
Abundance Table: abun.dat
Electron Temp:  10000.
Electron Density:  10000.
Inst. Resolution:     10.

ICF Values: Bin/%
ix 1:   0.00999999978
ix 2:   0.498415828
ix 3:   0.489584208
ix 4:   0.00100000005
ix 5:   0.00100000005

Velocity Structure: Bin/Vel(km/s)
irvcor 1:   4.26208973
irvcor 2:   4.08970976
irvcor 3:   1.74469769
irvcor 4:  -0.0550202653
irvcor 5:  -0.0550202653
```

Fig. 4.— The header for the **EMILI** output file generated by its run on the included data. Information regarding the input/output files, specified temperature, density, and instrumental resolution, is contained here, as are the values for the ICFs (labeled here as "*ix* 1" – "*ix* 5") and the velocity corrections (labeled here as "*irvcor* 1" – "*irvcor* 5") for the five ionization energy bins. No elements were depleted in this run.



```
Observed Line:   6347.19  5.1E-04  S/N:    83.30 FWHM:  47.7
   6347.15 |     6346.860  N  II      470862882    262  3.5E-04   13.8 5/0 8
   6347.19 |     6346.970  Mg II      806382603    262  1.0E-04   10.4 2/0 8
   6347.15 |     6347.030  Mn III    1680117006      6  1.3E-06    5.8 7/0 9
   6347.15 |     6347.030$ Ni II     1880698124      6  5.9E-06    5.8 0/0 7D
   6347.10 |     6347.014  Ca I      1342797915      7  9.5E-07    4.0 1/0 7D
+  6347.15 |     6347.110  Si II      940585992    262  6.7E-04    2.0 1/1 2A 6371.370   0.6
+  6347.15 |     6347.170* Si II      940655642      6  1.2E-04   -0.8 0/0 2A
+  6347.15 |     6347.230  Cl II     1142065248      6  1.0E-06   -3.6 3/0 7D
   6347.10 |     6347.243  Ca I      1342715984      7  1.0E-06   -6.8 1/0 8
   6347.10 |     6347.250$ Si I       940079130      6  2.8E-05   -6.9 0/0 6C
   6347.10 |     6347.330$ Si I       940078106      6  2.8E-05  -10.7 0/0 7D
   6347.15 |     6347.380  Ni II     1880493233      6  6.0E-06  -10.7 1/0 9
   6347.10 |     6347.340 [V  II]    1544610843     38  2.5E-05  -11.2 5/0 9
   6347.10 |     6347.346$ Fe I      1745668264      7  3.6E-05  -11.5 0/0 7D
   6347.10 |     6347.346$ Ni I      1879307325      7  2.0E-06  -11.5 0/0 8
   6347.10 |     6347.422  Ca I      1342798940      7  9.5E-07  -15.2 1/0 9
   6347.15 |     6347.543  Fe II     1746262248      7  2.7E-04  -18.4 6/0 8
   6347.15 | >   6346.560  Si II      940680287    262  1.1E-04   28.0 1/0 0<
```


Fig. 5.— An example of **EMILI** output from the *Full Output List* (**ic418.out**). This is an identification of a line observed at 6347.19Å (after correction to the nebular rest frame as established by the Balmer and Paschen series of Hβ. **EMILI** suggest that Si II λ6347.100Å is the most likely ID. This ID has a small residual wavelength difference (indicated by small value in km/sec in column **G**). It also has a *Template Flux* (column **F**) nearly the same value as what was observed (top line, second numeric value). An additional multiplet line, Si II 6371.370Å (column **J**), was found to correspond with another line in the *Input Line List* and indeed the code found the only other multiplet line it expected to find (column **H**). Thus, this putative ID did well (column **G**) with a low score and a primary ("A") ranking.

```
4058.29   4.2E-05   | N II  4058.16,
4065.23   5.5E-05   | Fe III  4065.25,
4067.33   3.6E-05   | [Fe III]  4067.30,
4068.67   1.8E-02   | [S II]  4068.60,
4069.63   2.0E-04   | O II  4069.62,
4069.89   2.0E-04   | O II  4069.88,
4072.15   3.3E-04   | O II  4072.15,
4074.51   1.0E-04   | C II  4074.48,
4075.89   4.4E-04   | O II  4075.86,
4076.37   7.6E-03   | [S II]  4076.35,
4078.81   5.6E-05   | O II  4078.84,
4079.64   2.5E-05   | [Fe III]  4079.70,
4082.32   5.3E-05   | N II  4082.27,
4083.87   4.8E-05   | [Fe II]  4083.78, O II  4083.90,
4084.67   4.7E-05   | [Co IV]  4084.59,
4085.10   7.6E-05   | O II  4085.11,
4087.15   4.5E-05   | O II  4087.15,
4089.29   1.1E-04   | O II  4089.29,
4092.92   3.2E-05   | O II  4092.93,
4093.92   4.9E-05   | N III  4093.68, Na I  4093.88,
4095.65   4.2E-05   | O II  4095.64,
4096.51   2.8E-05   | [Fe III]  4096.61,
```

A **B** **C**

Fig. 6.— A segment from a *Summary List* (**ic418.dat**). From left to right the columns are: **A.** a unidentified line's observed wavelength **B.** that line's measured flux with respect to Hβ **C.** the EMILI primary IDs (labeled "A" in the *Full Output List*) associated with the line.