the application of classical spectrum synthesis to the determination of Solar abundances
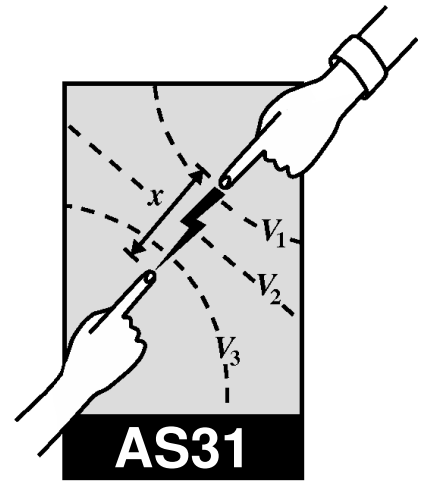
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AS31

1 Introduction

Solar abundances play a key role in astrophysics as they are the abundances relative to which all others are measured. Opacity is determined in metal-rich objects by the iron abundance and so if the solar iron abundance is incorrectly determined, opacity will be incorrectly calculated in these objects which means their evolution will not be as well-known as it should be. Another point is that meteoritic abundances, for those meteorites that originated in the Solar System, would be expected to be the same as those in the solar photosphere; if they are not there are consequences for our understanding of the formation of the Solar System.

Although classical spectrum synthesis was the method of choice when it came to measuring abundances of elements in the solar photosphere until the work of Asplund *et al.* (2000ab) and Asplund (2000) showed hydrodynamical calculations to be necessary if precise fits to solar line profiles are to be obtained, it had been known for sometime that the method was approximate because of asymmetries in observed line profiles. Nonetheless, classical spectrum synthesis remains a very good approximation and much can be learnt about stellar spectroscopy through its application. In the present experiment, you will derive the abundance of an element in the solar photosphere using a classical spectrum synthesis technique and then explore the limitations of the method from a study of work by Asplund *et al.* (2000ab) and Asplund (2000).

2 Initial setup

Begin by creating an `xterm` window in which commands can be typed. The window is created using the Mouse to click on the large "X" in the middle of the dock on the bottom of your screen. The large "X" may bob up and down a bit before the window appears.

The steps detailed below provide the setup necessary for experiments carried out in the Astrophysics Laboratory. The `.profile`, `.bashrc`, `.cups/lpoptions` and `.Xresources` files in your home directory are changed as a result of carrying out steps listed below; if these files have been previously setup to carry out an experiment in another laboratory, please consult a demonstrator before proceeding. If you have already carried an experiment in the Astrophysics Laboratory and the `.profile`, `.bashrc`, `.cups/lpoptions` and `.Xresources` files in your home directory have remained unchanged since, skip the steps below and move on to the next section.

Provide yourself with copies of the necessary `.profile`, `.bashrc`, `.cups/lpoptions` and `.Xresources` files by executing the commands

```
$ cp ~aelg/astro-lab/profile   .profile
```

```
$ cp ~aelg/astro-lab/bashrc    .bashrc
$ cp ~aelg/astro-lab/Xresources .Xresources
$ cp ~aelg/astro-lab/lpoptions  .cups/lpoptions
```

where the leading "$" represents the operating system command line prompt which by default is some long string. Once the above commands have been typed, logout and login again; this causes the .profile, .bashrc, .cups/lpoptions and .Xresources files to be executed and so providing the setup necessary to conduct experiments in the Astrophysics Laboratory. Create a new xterm window, as described above, in which commands can be typed; the first obvious sign of the new setup is the replacement of the default operating system command line prompt with a simple "$ ".

It is worth noting some unorthodox inputting methods inherent to Mac keyboards and mice. Some computers in the lab have mice with a right click feature (which is turned on in System Preferences). For mice without this feature (the clear ones), a right click can be emulated by using ctrl + left click.

3   Getting started

All computer commands reproduced below for your guidance are given in typewriter font. The leading "$" represents the command line prompt. A leading "> " represents a prompt provided by an executing program such as starspec. Typewriter font is also used to specify file names, file contents and environment variables. Further necessary information is provided in the Third Year Astrophysics Laboratory Practicals page

```
http://www-astro.physics.ox.ac.uk/~aelg/Third_Year_Laboratory
```

which can be read with a browser such as safari.

The first step is to create a new directory in which all files, associated with the experiment described here, will be stored. Issue a command of the form

```
$ mkdir as31
```

to create such a directory. Then type

```
$ cd as31
```

4   starspec

Solar spectra are synthesised using starspec, a command-driven program for the synthesis of stellar spectra assuming Local Thermodynamic Equilibrium (LTE). Available commands, parameters and default parameter values are summarised in appendices. This section is purely concerned with command syntax and program use.

Commands, parameter names and most parameter values can be typed in upper or lower case. One or more commands can be entered on a single line together with their associated parameters, if any. If more than one command is entered on a line, a comma must form the delimiter but otherwise free-format can

be used. As an illustration, a string of commands `Comm_1`, `Comm_2`, `Comm_3`, . . . , `Comm_n` can be entered as

```
> Comm_1, Comm_2, Comm_3, . . . , Comm_n
```

and each command will be executed in the order given. Parameters have not been given and so defaults (or current settings) are used where available; where there is no value available the user is prompted for it by having the parameter name supplied as a prompt. In certain cases, such as the HELP command, the associated parameter is reset after each call so that all help information is given by default.

The easiest way for a user unfamiliar with the program to check parameter assignments for a command to be executed is to type the required command and follow it with a query. As an illustration

```
> Comm_3 ?
```

results in the program prompting for values of all parameters associated with this command, supplying existing values (if any) with the parameter name.

Parameters can also be assigned values either by having the parameter name and value associated with an equality, or by simply specifying a value; in this latter case the default order of parameters associated with the command is assumed. Free format is again permitted, and any number of spaces can be used on either side of an equality associating a parameter and the supplied value. As an illustration, consider

```
> comm_1 param_1=value_1 param_2=value_2, comm_1 value_1a
```

where the second execution of "comm_1" is with "param_1" having a value "value_1a" instead of "value_1", whereas "param_2" is unchanged. Alternatively, parameters can be assigned values without a command specification. For instance

```
> param_1=value_3, param_2=value_4, . . .
```

where parameter assignments are treated as commands.

See the appendices at the end of this script for an alphabetic listing of commands and parameters. Associated with the description of each command is a list of the required and optional parameters it takes. After the list of commands is an alphabetic list of parameters and a description of each one. Default values of parameters are also presented where these exist.

5 Atomic data

Atomic data for spectrum synthesis calculations are to be found in the directory `~aelg/solar_abundances/loggf` in files whose names, for the lines of neutral atoms, are the corresponding chemical symbol followed by a dot. In the case of once ionised species, the "." is followed by a "1", for twice ionised species a "2" and so on. A demonstrator will allocate an element (titanium, chromium or iron) whose abundance in the solar photosphere is required. Copy the file for the neutral species into your working directory using, in the case of chromium, the command

```
$ cp ~aelg/solar_abundances/loggf/CR. .
```

and examine it using a text editor. The first record is simply a header, informing the reader of the species to which the line data apply. Data are then tabulated in five columns; these are terminated by a blank record to which reference records are appended. The five columns are wavelength (Å), excitation potential of the lower level (in electron volts), $\log gf$, damping enhancement factor and number of the reference (listed at the end of the file) from which the data are taken; here g is the degeneracy of lower level and f is the oscillator strength. Changes to the damping enhancement factor will be needed and have to be entered into your copy of this file; in making such changes, it is essential to ensure that the column alignment is preserved.

6 The solar spectrum

The next step is to examine the solar spectrum and identify lines to be used in the abundance analysis. Three atlases of solar spectra are provided for use in this experiment although it is suggested that use be made of only one of them. Delbouille *et al.* (1973) publish an atlas of specific intensities measured at the centre of the solar disk. Kurucz *et al.* (1984) provide a flux atlas where the fluxes are obtained by integrating the specific intensity over the solar disk for each wavelength point; this is in effect what would be observed if we were so far from the Sun that it appeared as a point source. The infrared atlas by Farmer & Norton (1989) shows a number of molecular features not observable from the ground.

In order to examine available spectra, change your current directory to be the same as that in which the spectra are stored. Issue the command

```
$ cd ~aelg/solar_abundances/solar_spectra
$ ls
```

will show you the three sub-directories in which Delbouille *et al.* , Kurucz *et al.* and Farmer & Norton spectra are stored. Use the commands

```
$ cd delbouille
$ ls
$ cd ../kurucz
$ ls
$ cd ../atmos
$ ls
```

to examine the contents of each directory in turn. Files in each sub-directory have names separated by "–"; these indicate the wavelength range covered by data. For Farmer & Norton ATMOS spectra the wavelength range is expressed in microns; in the other two cases, it is expressed in Ångstroms.

Each file is binary and can be read and plotted using the program DIPSO. Within DIPSO the command to use is sp0rd. Full documentation for a more recent version of DIPSO is referenced in

```
http://www.starlink.rl.ac.uk/star/docs/sun50.htx/sun50.html.
```

An alternative to using DIPSO to display parts of the solar spectrum is to use starspec, the spectrum synthesis program. For example, to display the Delbouille *et al.* specific intensity atlas between 5001 Å and 5121 Å in three successive plots type

```
$ starspec
  >oppdev xwindow
  >robspc i-5001-5041-c.dat, plot
  >robspc i-5041-5081-c.dat, plot
  >robspc i-5081-5121-c.dat, plot
  >q
```

when in the appropriate sub-directory. Now suppose you are working on the chromium abundance using neutral chromium lines and wish to consider using the lines at $\lambda\lambda$ 5204.52 Å, 5206.04 Å and 5208.44 Å; one way of using starspec to examine these lines in high resolution is to first copy the file I-5201-5241-C.DAT into your working directory and then when in that directory type

```
$ starspec
  >oppdev xwindow
  >robspc i-5201-5241-c.dat, plot, cursor
```

with the added cursor so that an interactive graphics cursor is presented. Move the cursor with the mouse to the circle adjacent to the "Expand plot" option and press the left hand mouse button. Then select two wavelength limits, in this case 5204 Å and 5209 Å should suffice, by again moving the cursor with the mouse and pressing the left-hand button. After two presses of the left-hand mouse button you will be advised of the wavelength limits selected; if you are dissatisfied, repeat the process, selecting the wavelength limits in either order. Once satisfied, press the right hand mouse button and your graph will be redrawn using the new wavelength limits.

Wavelengths of spectral features can be interactively measured by using the mouse to move the cursor to the circle adjacent to the "Measure wavelength" option and pressing the left-hand mouse button. The mouse can then be used to move the cursor to each spectral feature in turn, its wavelength is returned on pressing the left-hand mouse button; wavelength measurement is terminated by pressing the right-hand mouse button. Return to keyboard control by using the mouse to move the cursor to the circle adjacent to the "Return to keyboard control" option and press the left-hand mouse button. The cursor options "Change abundance". "Change oscillator strength" and "Change line damping" are not yet implemented.

A hard copy of any plot of interest can be made by selecting postscript instead of xwindow. If a plot has already been displayed using xwindow, generate a postscript file using the starspec commands

```
  >oppdev postscript, plot, oppdev xwindow, plot
```

which will recreate the xwindow plot once the postscript plot has been made. Postscript output is contained in a file called pgplot_nnnnn.ps (nnnnn being the file version number) written to the current working directory. It is possible to spawn an xterm shell from within starspec by using the spawn command; the hard copy can then by viewed and printed using the commands (using the first postscript output as an example)

```
$ open pgplot_00001.ps
$ lpr -o raw pgplot_00001.ps
```

and you return to the starspec session by typing control-d. The first command previews the postscipt file, though replace "open" with "gv" if you are working remotely.

An alternative to using the graphics cursor to expand plots of spectral regions is to supply wavelengths as arguments to the `starspec` command `plot`. The arguments are called `xplmin` and `xplmax` and can be prompted for, as with all `starspec` commands, by following the command with a "?". Current values are included in the prompt itself within parenthesis and if these are acceptable, simply press return rather than type in a value. Values of `xplmin` and `xplmax` of zero imply that the full wavelength range is plotted.

Examining the plot of the three neutral chromium lines, it can be seen that all three lines are quite strong and may not therefore be good abundance indicators as they are likely to lie on the damping part of the curve-of-growth. The line at $\lambda 5204.52$ Å otherwise appears to have a fairly clean blue wing but care would need to be taken with the red wing where there is evidence of blending. The other two lines appear to be heavily blended and are of doubtful value in an abundance determination. On the other hand all three lines, in a relatively short wavelength region such as this, could be synthesised together and something learnt about the blended features as a consequence.

Using criteria such as those described in the previous paragraph, look at spectra to select ten lines for abundance measurement. Avoid lines that are weak because these are more susceptible to blending from unknown sources. Similarly, avoid lines which are obviously strong as these will have strong damping wings which will prove difficult to fit and even then could result in an unreliable abundance. It is also a good idea to select lines which appear to have symmetric profiles and a well defined continuum on either side; these will be in parts of the spectrum which are not crowded with adjacent lines. The material presented for marking must include a justification for all lines chosen for an abundance determination.

7 Model stellar atmospheres

Temperature, gas pressure and electron density in a stellar atmosphere determine the degree of ionisation, degree of association into molecules and level populations for all species. Of course temperature, gas pressure and electron density are all depth-dependent as is the monochromatic optical depth at any wavelength. In order to calculate the emergent stellar spectrum, as well as specifying element abundances and line data as already described, a model stellar atmosphere is needed; this gives variation of temperature, gas pressure and electron density with depth.

Three models of the solar atmospheres are provided for the experiment. All are to be found `~aelg/solar_abundances/` which contains a directory `model_atmospheres`. It is recommended that you use the empirical model by Holweger & Müller (1974) and this is in the file `HM.MODEL` because experience has shown that this is superior to any computed model stellar atmosphere. The model in `ASUN.DAT` is computed by Kurucz (1993) and other in `BELCRD.DAT` calculated using the program MARCS by Gustafsson *et al.* (1975).

8 Spectrum synthesis

The use of `starspec` to measure solar abundances is best demonstrated by example and it is suggested that you work through this example even if you are not setting out to determine the chromium abundance. Suppose the abundance of chromium is being measured and it is to be based on the specific intensity spectrum of Delbouille *et al.* (1973); specifically the line λ 5783.93 Å is to be used. The first step would be to use `starspec` to read that part of the Delbouille *et al.* (1973) atlas between 5761 Å and 5801 Å and plot the region between about 5783.7 Å and 5784.2 Å using

```
$ starspec
 >oppdev xwindow
```

```
>robspc i-5761-5801-c.dat
>plot xplmin=5783.7 xplmax=5784.2
```

which shows immediately that the line is blue-shifted. Use the graphics cursor to measure the line wavelength; this should turn out to be 5783.86 Å, a shift of -0.07 Å which corresponds to -3.628 km/s. The shift is due to a combination of the Sun's gravitational redshift and convective flows in the solar photosphere; it needs to be removed for classical spectrum synthesis, so read the observed spectrum again using the appropriate velocity shift and replot. The starspec commands are

```
>robspc vshift=-3.628
>plot
```

where the file name and wavelength limits for plotting are unchanged and so do not need to be entered again.

The model stellar atmosphere can now be read, and the element whose abundance is required established using

```
>rmodel modfilei=hm.model origin=holmul xmicro=1.0
>set element=cr
```

where a microturbulence velocity of 1 km/s has been assumed; this is not necessarily the best value and you are advised to seek guidance from Blackwell *et al.* (1996) and justify your choice in the material submitted for marking. The next step is to read in the line list and compute the continuum specific intensity using

```
>rlines compiler=oxford linfile1=* wavehi=5784.20 wavelo=5783.71
>continuum nwavei=499 costheta=1.0
```

which specifies that the continuum (and synthetic spectrum) is to be computed in steps of 0.01 Å from 5783.71 Å to 5784.20 Å inclusive; this corresponds to 500 wavelength points or 499 wavelength intervals. On no account must the number of wavelength intervals (nwavei) exceed 2999, as 3000 wavelength points is the maximum permitted by array sizes in the program. When observations are made at the centre of the solar disk, the emergent radiation seen by the observer is normal to the solar photosphere; this is set using costheta=1.0.

Finally the synthetic spectrum can be computed and plotted in red for comparison with the observed spectrum using

```
>cspectrum
>plot graph=comparison
```

which is a hopeless fit because the default chromium abundance in the program is much too high. So the obvious next step is to reduce the chromium abundance, recalculate the synthetic spectrum and replot with

```
>change eabund=6.0
>rmodel,rlines,continuum,cspectrum,plot
```

where it should be noted in particular that the model atmosphere and line list need to be read again so as to ensure that the equation of state and line opacities are updated to take account of the new abundance. The chromium abundance is still clearly too high, on reducing it further

```
>change eabund=5.5
>rmodel,rlines,continuum,cspectrum,plot
```

it is now too low because the equivalent width (or area) of the theoretical line profile is less than that of the observed line profile. Notice also that the theoretical profile is much narrower than the observed profile; this is because broadening due to solar rotation, macroturbulence and the spectrograph (instrumental broadening) have not been taken into account. So we now broaden the profile and plot again using

```
>spsmear insfwhm=0.07 limbdark=0.1 vsini=2.0
>plot
```

and it is now quite clear that the computed profile is too weak. The resolution of the spectrograph used by Delbouille *et al.* is wavelength dependent but is typically 0.01 Å and the rest of the 0.07 Å full width at half maximum (FWHM) of the Gaussian broadening function is due macroturbulent motions in the solar photosphere. Limb darkening is not an issue when observing at the centre of the solar disk and the value specified is irrelevant. The other source of broadening is solar rotation which is 2 km/s at the solar equator, but this too is unimportant when working with the Delbouille *et al.* specific intensity atlas.

The abundance is therefore increased again and the resulting comparison plotted with

```
>change eabund=5.9,rmodel,rlines,continuum,cspectrum,spsmear,plot
```

and an inspection shows that the line is now broadened too much. So we reduce the macroturbulence and make a fine adjustment to the abundance with

```
>change eabund=5.88
>rmodel,rlines,continuum,cspectrum,spsmear insfwhm=0.06,plot
```

and it is now quite clear that the velocity shift applied to the observed spectrum is not as good as it might have been and so this is refined as the next step

```
>robspc vshift=-3.8,plot
```

which shows that a further reduction in the macroturbulence broadening is necessary; making this with the corresponding adjustment to abundance

```
>change eabund=5.815
>rmodel,rlines,continuum,cspectrum,spsmear insfwhm=0.05,plot
```

gives what appears to be an excellent fit to the blue-wing except where it merges with the continuum.

Damping is calculated in `starspec` in the hydrogenic approximation which is known to seriously underestimate the effect (see Page 74 of Rutten's lecture notes referenced in `http://www-astro.physics.ox.ac.uk/~aelg/Third_Year_Laboratory`). Enhancement factors for the Van der Waal's interaction constant (C_6) are initially set to unity in the fourth column of the data file; by experimentation it can be established that thirty-five gives a much better fit to the far blue wing of Cr I λ5783.9Å. After editing the data file, necessary changes made with the `starspec` commands

```
>change eabund=5.730
>rmodel,rlines,continuum,cspectrum,spsmear insfwhm=0.02,plot
```

result in an excellent fit to the blue-wing but a poor fit to the red wing. Plotting residuals with

```
>plot graph=differences
```

shows that the poor fit to the red-wing could be the result of a blend. Note that even for the blue-wing where the fit appears to be excellent, it is in reality quite poor; the χ^2 calculated for the blue-wing is a factor of ten larger than it should be, given that the signal-to-noise in the observed spectra is 5000 or higher. Moreover, blue-wing residuals show a clear trend with wavelength indicating that the theory used is simply not good enough. Nonetheless, the technique used here was "state-of-the-art" until a decade ago.

The aim of the experiment is to derive an abundance for each of the ten lines you have chosen for the element of interest, following the technique described in this section. In addition to deriving an abundance, determine the C_6 enhancement factor in each case. Material submitted for marking should include plots showing the comparison between observed and synthetic line profiles, as well plots of the "observed minus synthetic" residuals, in each case. Plots need to be annotated with the abundance, the FWHM of the Gaussian broadening function, the C_6 enhancement factor, the velocity shift applied to the observed spectrum and the microturbulence velocity; your estimate of the error in each case is also needed.

9 Interpretation

The first step is to calculate the mean abundance for all lines used and its standard deviation. If any line is found to give an abundance more than two standard deviations away from the mean, it needs to be looked at again and if necessary replaced by another line. Next estimate the standard deviation in the abundance obtained for each individual line resulting from the fitting process; to a reasonable approximation this will be ± 0.01 dex but check this by inspection of all plots of "observed minus synthetic" residuals and perturbing the fit of at least one line. Next compare the abundance standard deviations of individual lines with the standard deviation of the mean abundance; the latter should be about a factor of three smaller than individual line standard deviations, and if not a comment is needed.

If the dependence of temperature, gas pressure and electron pressure on depth in the solar atmosphere has not been correctly estimated then derived abundances will be correlated with the excitation potential of the lower level involved in the corresponding line transition. An easy way to make a plot and statistically test the correlation, if any, between abundance and excitation potential is to use your text editor to create a two-column file (excitation potential in the left-hand column and abundance in the right-hand column with spaces rather than tabs separating the columns) which is first read into DIPSO and then into CORCOEFF. The correlation coefficient measuring the dependence of a discrete variable y_i $(i = 1, 2, \ldots, n)$

on another discrete variable x_i is given by

$$r = \frac{\sum\limits_{i=1}^{n} (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum\limits_{i=1}^{n} (x_i - \overline{x})^2 \sum\limits_{i=1}^{n} (y_i - \overline{y})^2}}$$

where perfect correlation corresponds to $r = 1$, perfect anti-correlation to $r = -1$ and no correlation to $r = 0$. Of course, it does not suffice to calculate the correlation coefficient (r); it is also necessary to estimate the significance level at which the null hypothesis of zero correlation is disproved.

A script is available to facilitate the use of DIPSO; copy it into your working directory using the command

```
$ cp ~aelg/solar_abundances/dipso_script/abundance_vs_excitation_plot.cmd P.CMD
```

and review its contents. The script, now called `P.CMD` in your directory, is written assuming that data (excitation potentials and abundances) are in a file called `expot.dat`; if your file is called by any other name, a change needs to be made to `P.CMD`.

A screen plot of abundance against excitation potential is then invoked by typing

```
$ dipso
>@P
```

and when ready type

```
>q
```

to leave DIPSO. After making the change described in comments embedded in `P.CMD`, the same sequence of commands produces a postscript file containing the abundance against excitation potential plot, which may then be printed as previously described.

The linear correlation coefficient and significance at which the null hypothesis of zero correlation is disproved may be calculated with the sequence of commands

```
$ DIRECTORY='pwd' ; export DIRECTORY
$ INPUTFILE=expot.dat ; export INPUTFILE
$ corcoeff
```

where 'pwd' substitutes the output of the `pwd` (print working directory) command. In the above sequence, if the abundances and corresponding excitation potentials are in a file with a different name, then use that name instead of `expot.dat`. Make a note of the correlation coefficient obtained and the significance level at which the null hypothesis of zero correlation is disproved; this last number needs to be very small, ($\leqslant 0.01$) for a 99% confidence that a correlation exits. Provide a sentence to discuss the results obtained, and deduce whether the temperature, gas pressure and electron pressure dependence on depth in the model solar atmosphere are correctly estimated or not.

Comments on how abundance determinations are compromised by the necessary (if the practical is to be accomplished in two days) neglect of the hydrodynamical effects described by Asplund *et al.* (2000ab)

and Asplund (2000) are needed in addition. It is also useful to compare your abundance determinations with those of Allende Prieto *et al.* (2001) and, in case of iron, with Bellot Rubio & Borrero (2002). As a final step, correct your derived mean abundance for the effects of granulation using tables by Steffan & Holweger (2002).

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A   STARSPEC Commands

- CHANGE - Change selected element abundance and optionally its isotope ratio or an associated isotope abundance.
  Parameters: EABUND

- CLPDEV - Closes and deactivates a named GKS Workstation ie. releases a previously used graphics device.
  Parameters: DEVICE NDEVICE

- CONSMP - Displays total and elapsed (since previous execution of this command) CPU time, buffered I/O count, direct I/O count, page faults, peak working set size and current working set size.

- CONTINUUM - Compute continuum fluxes.
  Parameters: NWAVEI WAVEHI WAVELO WUNITS COSTHETA

- CSPECTRUM - Compute synthetic spectrum.
  Parameters: NORMALISE

- CURSOR - Passes control to graphics cursor.

- HELP - Provides general help information with a description of all commands and parameters when typed without the optional parameter, and specific help on a chosen subject (command or parameter) when typed with the optional parameter.
  Aliases: EXPLAIN EXPL ?
  Parameters: SUBJECT

- LIST - Lists available commands or parameters on terminal.
  Parameters: ITEM

- OPPDEV - Opens and activates a named GKS Workstation ie. prepares a graphics device for output.
  Parameters: DEVICE NDEVICE

- PLOT - Displays input spectrum on previously opened GKS graphics device(s). Entire spectrum is displayed if limits are not specified.
  Parameters: GRAPH XPLMIN XPLMAX

- RESTORE - Recover previously saved synthesis session.
  Parameters: SAVEFILE

- RLINES - Reads selected line lists and computes line opacities for depths and wavelengths.
  Parameters: COMPILER LINFILE1 LINFILE2 WAVEHI WAVELO

- RMODEL - Reads model stellar atmosphere and computes number densities for currently selected species.
  Parameters: MODFILEI ORIGIN XMICRO XISOTOPE

- ROBSPC - Reads a SPECTRUM/DIPSO format file in BINARY (type 0) or ASCII (type 2).
  Parameters: INFILE INFORM VSHIFT

- SAVEIT - Save current synthesis session for later recovery.
  Parameters: SAVEFILE

- SPAWN - Spawns a subprocess.

- SPSMEAR - Broadens synthetic spectrum by rotation and instrumental profiles.
  Parameters: INSFWHM VSINI LIMBDARK

- SET - Select an element and perhaps a specific isotope of that element, for abundance adjustment.
  Parameters: ELEMENT ISOTOPE AFORM

- STOP - Terminates program execution.
  Aliases: QUIT END Q

- WCNTUUM - Writes continuum fluxes, or specific intensities if these were calculated, to SPEC-TRUM/DIPSO format file in BINARY (type 0) or ASCII (type 2).
  Parameters: OTFILE OTFORM TIMEHED

- WMODEL - Write model stellar atmosphere for STARLINE use. Parameters: MODFILEO

- WSYNTHS - Writes synthetic spectrum to a SPECTRUM/DIPSO format file in BINARY (type 0) or ASCII (type 2).
  Parameters: OTFILE OTFORM TIMEHED

- @ - Indicates that commands in the specified file are to be executed as though they formed a single command.
  Syntax: @comfile
  Parameters: COMFILE

B   STARSPEC Parameters

- AFORM - Form of element abundance specification.
  Default: H12
  Legal Values: H12 NUMBERS

- COMFILE - Name of file from which commands are to be read.
  Default: None

- COMPILER - Origin of line list to be used for synthesis.
  Default: None
  Legal Values: BELL KURUCZ OXFORD

- COSTHETA - Cosine of angle at which emergent specific intensity is calculated. A value greater than one implies 1.0 (centre of disk) and a value less than 0.01 implies 0.0 which gives an emergent physical flux calculation.
  Default: 0.0

- DEVICE - Name of graphics device to receive output.
  Default: None
  Legal Values: XWINDOW INKJET PRINTRONIX POSTSCRIPT ZETA
  PERICOM T4010 IKONVT IKON CANON

- EABUND - Abundance of selected element. This abundance is to be adjusted to fit synthetic to observed spectrum.
  Default: 0.0

- ELEMENT - Element whose abundance is to be adjusted.
  Default: C
  Legal Values: H HE C N O NE NA MG AL SI P S AR K CA SC TI V CR MN FE NI

- GRAPH - Type of graph to be plotted.
  Default: INPUT
  Legal Values: COMPARISON DIFFERENCES INPUT

- INFILE - Name of SPECTRUM/DIPSO file to be read.
  Default: None

- INFORM - Format of SPECTRUM/DIPSO file to be read.
  Default: BINARY
  Legal Values: ASCII BINARY

- INSFWHM - Instrumental profile full width at half maximum in Ångstroms.
  Default: None

- ISOTOPE - Isotope of selected element whose abundance is to be adjusted. Individual isotopes are ignored if zero.
  Default: 0

- ITEM - Select list of available commands or parameters.
  Default: COMMAND
  Legal Values: COMMAND PARAMETER

- LIMBDARK - Limb darkening coefficient used in the Eddington approximation adopted in calculation of rotation profile.
  Default: 0.0

- LINFILE1 - Principal line list file name.
  Default: None

- LINFILE2 - Secondary line list file name. A single asterisk indicates that no secondary file is to be read.
  Default: *

- MODFILEI - Name of file containing model atmosphere.
  Default: None

- MODFILEO - Name of file receiving model atmosphere.
  Default: None

- NDEVICE - No. of graphics output devices to be available. Any positive integer is acceptable.
  Default: 01

- NORMALISE - Indicates whether or not the synthetic spectrum should be normalised.
  Default: .TRUE.
  Legal Values: .TRUE. .FALSE.

- NWAVEI - No. of wavelength intervals in synthetic spectrum Any positive integer is acceptable.
  Default: 01

- ORIGIN - Origin of model stellar atmosphere to be read.
  Default: ATLAS6
  Legal Values: ATLAS6 MARCS QUB HOLMUL

- OTFILE - Name of SPECTRUM/DIPSO file to be written.
  Default: None

- OTFORM - Format of SPECTRUM/DIPSO file to be written.
  Default: ASCII
  Legal Values: ASCII BINARY

- SAVEFILE - File in which work is saved for later recovery.
  Default: None

- SUBJECT - Command or parameter for which help information is required. By default all help information is listed.
  Default: None

- TIMEHED - Determines whether header for output file is constructed from date and time or copied as input.
  Default: .TRUE.
  Legal Values: .TRUE. .FALSE.

- VSHIFT - Radial velocity shift to be applied to observed spectrum.
  Default: 0.0

- VSINI - Projected stellar rotation velocity used in computation of rotation profile (kms/sec).
  Default: 0.0

- WAVEHI - Red limit of synthetic spectrum.
  Default: None

- WAVELO - Blue limit of synthetic spectrum.
  Default: None

- WUNITS - Units in which WAVEHI and WAVELO are to be given.
  Default: AANGSTROMS
  Legal Values: AANGSTROMS MICRONS MM NM

- XISOTOPE - Determines whether isotopes are to be treated as individual species.
  Default: .FALSE.
  Legal Values: .TRUE. .FALSE.

- XMICRO - Microturbulence velocity in km/s.
  Default: 0.0

- XPLMIN - Minimum abcissa to be plotted.
  Default: 0.0

- XPLMAX - Maximum abcissa to be plotted.
  Default: 0.0