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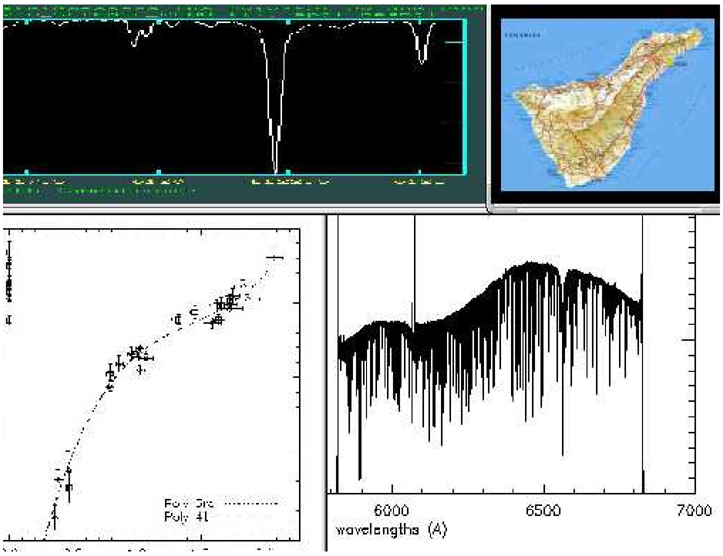

Calibration of effective temperature of solar type stars, using equivalent width ratios of spectral lines

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Abstract

The effective temperature is one of the fundamental stellar parameters used to derive many quantities in astrophysics. Reducing the error bars on this variable will improve our knowledge on stellar properties.
In this report, we expose an accurate calibration method for effective temperature determination of solar-type stars, using equivalent width ratios of spectral lines. We have computed a list of 250 temperature sensitive line ratios made of 142 spectral lines from 14 different chemical elements. We have used 38 solar-type calibration stars, which temperatures have been homogeneously determined using stellar atmosphere models. We have fitted our calibration curves using 3^{rd} and 4^{th} order polynomial functions.
We have obtained 113 calibrations curves with small dispersion, of which 12 have very a large dynamical range in temperature.
The accuracy of our calibration curves can still be improved using more precised equivalent width measurements, larger sample of calibration stars, and other type of fitting funtions. Those improvements are under process.

La température effective est un des paramètres stellairs fondamentaux, utilisés dans de nombreuses équations en astrophysique. Diminuer les incertitudes associés à cette variable nous permettra d'améliorer notre connaissance sur les propriéts physiques des étoiles.
Dans ce rapport, j'expose une méthode pour calibrer la température effective des étoiles de type solaire. Cette méthode utilise la sensibilité des rapports de largeures équivalentes de raies spectrales comme sonde de température. Nous avons contruit 250 rapports de raies ayant une bonne sensibilité à la température. Ces rapports de raies sont réalisés à partir d'une liste de 142 raies spectral appartenant à 14 différents éléments chimiques. Pour réaliser cette calibration, nous avons utilisé 38 étoiles de type solaire. Nous avons ajusté nos courbes de calibration à l'aide de fonctions polynomiales d'ordre 3 ou 4.
113 courbes de calibrations, présentant de faibles dispersions, ont été obtenues. Parmis celles-ci, 12 présentent une bonne sensibilité sur une large plage de température.
La précision de nos courbes de calibration peut être améliorée en mesurant les largeures équivalentes avec plus grands soins, en utilisant davantage d'étoiles pour construire notre calibration, et en ajustant nos données par d'autres type de fonctions. Ces améliorations sont actuellement en cours.

La temperatura efectiva es uno de los parámetros estelares fundamentales que usamos en muchas ecuaciónes en astrofísica. Si reducimos las barras de errores en temperatura, podriamos mejorar nuestro conocimiento de las propiedades estelares.
En este informe, exponemos un método para calibrar la temperatura efectiva de las estrellas de tipo solar. Este método calibra la temperatura en función de la razón de anchuras equivalentes de las lineas espectrales. Hemos analizado una lista de 250 razones sensibles a la variación de temperatura, compuestas por 142 lineas espectrales de 14 diferentes elementos químicos. Disponemos de 38 estrellas de calibración de tipo solar, cuyas temperaturas han sido homogeneamente determinadas usando modelos de atmósferas estelares. Las curvas de calibración se han ajustado usando funciónes de 3^{ro} y 4^{to} orden.
Hemos obtenido 113 curvas de calibración con pequeñas disperciónes, de las cuales 12 presentan un rango de sensibilidad en temperatura bastante grande.
Nuestras curvas de calibración aún pueden ser mejoradas utilizando medidas de anchuras equivalentes mas precisas, un mayor numero de estrellas de calibración, y otros tipos de ajustes. Estas mejorías están actualmente en proceso.

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Contents

Chapter 1

Introduction

This report is about calibration of effective temperature using equivalent width line ratios. Before explaining the method used, lets settle down the subject and have a look at why this work is of any interest.

1.1 The interest in effective temperature measurement

The effective temperature is one of the fundamental basic stellar parameters and is used in many equations in astrophysics.

As errors propagate in the equations, decreasing the error on effective temperature can improve significantly the precision on other astrophysical parameters, like for abundances calculations for instance. So far, we have been dealing with temperature error bars of around 50 K, down to 20 K in some cases (Santos 2004,2006, Gray 1989). Now, we are trying to decrease those errors even more, down to 10 K.

There are numerous way to derive the effective temperature of a star. One can achieve it using spectroscopic or photometric data.
The method investigated in this report uses spectral line ratios as a probe of temperature. This method has already been used by many authors, such as D. Gray (1994), V. Kovtyukh et al. (2003), B. Caccin et al. (2002), K. Biazzo et al. (2004).
The calibration method using line ratios has been found to be quite efficient on temperature variations measurements. In this method one of the main difficulties is to determine the zero point (i.e the origin of the line ratio axis). For F,G,K stars, the sun is an excellent calibrator to determine the zero point. But it is not valid to calibrate effective temperature of giant stars for instance.
Moreover, the temperature calibration is not valid for extrapolation. The derived calibration curves should only be applied to stars of the same type as the calibrators: F,G,K stars in this report.

1.2 The calibration method

The calibration method discribed in this report uses equivalent width line ratios. The particularity of this project is to compute temperature with better precision, using a wide number of ratios as well as high quality spectra (high signal to noise ratio and high resolution) from an homegeneous stellar sample.

This calibration method improves the temperature measurement by providing several independent measurements of the effective temperature, using the same data set. Indeed, measuring a quantity N times will reduce the average error by a factor $\sqrt{N}$. For instance, when using 50 calibration curves to derive the effective temperature, one reduces the error by a factor 7, i.e if the initial error was 50 K, the final error would be 7 K.
Measuring the temperature using different line ratios is also a way to check the consistency and the uniqueness of the calibration set. This is a way to test the non dependence of the derived temperature with regards to the chimicak elements or the spectral range used in the ratios.

1.2.1 Equivalent width and line depth

In the previous work investigating calibration of effective temperature, the authors have used line depth ratios to probe temperature variations. In this report, we are using equivalent width ratios.

The line depth is the depth of the spectral line. To measure the line depth, different method were used : the old method was to use a simple ruler (Gray and Johanson 1991), the modern one is to use gaussian fittings (Kovtyukh et al. 2003). The height of the gaussian is the measure of the line depth. The only requirement is to use high resolution spectra, as one seeks high precisions to determe the minimum of the spectral line.

The equivalent width is the area (in $m\AA$) of the spectral line. The main advantage of using equivalent width is to be able to measure it even using low resolution spectra. One disadvantage is that equivalent width measurement is more affected by the continuum uncertainty. Indeed the equivalent width is an integral over range of wavelength, which means that it also sums the continuum uncertainty over this range, wherase the line depth is affected only on one unit of wavelength. For this reason, stronger lines have larger uncertainty on their equivalent width measurement. Another disadvantage of using equivalent witdh appears when dealing with blended lines as additional uncertainties are introduced.

The reason why line depth have been prefered to equivalent witdh is mainly because of blended lines. Indeed, when a line is blended, even when the cores are unblended, it is difficult to separate the the contribution of its equivalent width from the one of the other line(s). Therefore, we introduce new errors in our equivalent width measurement. When dealing with line depth, only the cores of the lines need to be unblended.

Nevertheless, above all, the big advantage of using equivalent widths instead of line depths, is the possibility of measuring equivalent widths in an automated manner, using various softwares (in this project: DAOSPEC). This is a substancial gain of time, which allows work on larger star sample and on more ratios at the same time. Thus, even if we lose precision on individual temperature estimations, we improve the quality of our calibration by multiplying the measurements.

1.2.2 Advantages of using line ratios

As in a given spectrum, spectral lines are similarly shaped by rotational and microturbulence broadening, and by spectral resolution and interstellar reddening, those effects cancel out when using line ratios (Gray 1991, Kovtyukh 2003). Thus, line ratios are not sensitive to those kind of astrophysical or instrumental line distortions.
Equivalent width ratios are also independent on chimical compositions, i.e on line strengths, as long as the two lines are from chimical elements showing similar abundance behaviours with regards to metallicity. We have been considering this metallicity dependance when building our line ratios, as we will see in the following chapter.

1.2.3 Chimical abundances

The abundance in a given chimical element X, noted [X/H], represents the abundance of the element in comparison with the abundance of hydrogen H in the object of study. This quantity can be calculate as followed :

$$[X/H] = \log{(N_X/N_H)_\star} - \log{(N_X/N_H)_\odot} \tag{1.1}$$

where N is the number (in unit volume) of atoms, * is the star of study, and $\odot$ is the sun.

Chapter 2

Selection of the line ratios

The project can be divided into 3 main steps : selecting the spectral lines and building the ratios, measuring the equivalent widths, and combining the two to build the calibration curves.

The effective temperature calibration is realised using plots of effective temperature against line ratios. The effective temperature of the calibration stars come from an homogeneous sample derived by Santos et al. (2004,2005). We had to first build the ratios and then apply them to our first sample of 38 stars. To build the ratios, we had to find the appropriate lines and the suitable combination of lines. This is an important step, explained in the next section. Then, we had to mesure the equivalent width of each of those lines for each of the stars of the sample. This is a quite tedious work to be done manualy, so we used a software called DAOSPEC which measure automaticaly all the equivalent width of the line list given in input. The next step was to compute de ratios with those measurements and to plot the calibration graphs. The last step was to find the suitable function to fit those plots.

2.1 Line ratios

2.1.1 Selection of the lines

The first step of my work was to select the lines we will used to build the ratios.

The lines were taken from a list composed of 148 spectral lines provided by V. Kovtyukh, 39 FeI lines used by N. Santos to compute stellar atmosphere parameters (Nuno 2004), and 80 lines used by G. Gilli to compute stellar abundances (Gilli 2006). All thoses lines are located between 5200 and 6800 $\mathring{A}$, have excitation potentials between 0.8 and 5.9 eV, and are in spectral regions far from telluric absorption.

We have chosen to work with wavelengths between 5200 and 6800 $\mathring{A}$ for two reasons, a naive one and a pratical one. This study is our first steps in building line ratios for temperature calibration, and to start somewhere we started with Kovtyukh's range in wavelength. This was the naive reason. The practicle one is because we have a wide sample of stellar spectra covering this range of wavelengths.

The first creteria we wanted our lines to fullfill regarded the blendings. Indeed, as we are working with equivalent width and not line depth, we have to be carefull with blended lines. We choosed to keep only the unblended or well blended lines. What we mean here by well blended is when the line cores are unblended, even if the line wings overlap. We have annotated the well blended lines to allow follow up of the ratios involving them and check if there are any dispersion excess in this calibration plots.
To know if the lines were bad, well or not blended (see example on FIG.2.1), I have had to check them manually on the spectra of HD59686 a 4871 K and [Fe/H]=0.28 star, using the SPOLT task of IRAF[1]. As the blending is meant to be worse in cool metal rich stars, this test tells us about how much blended thoses lines can be in our sample. Of course, this is only to be taken as an indicator, as higher resolution spectra can reveal unidentified bad blended line, and as some lines can become blended at higher metallicity.

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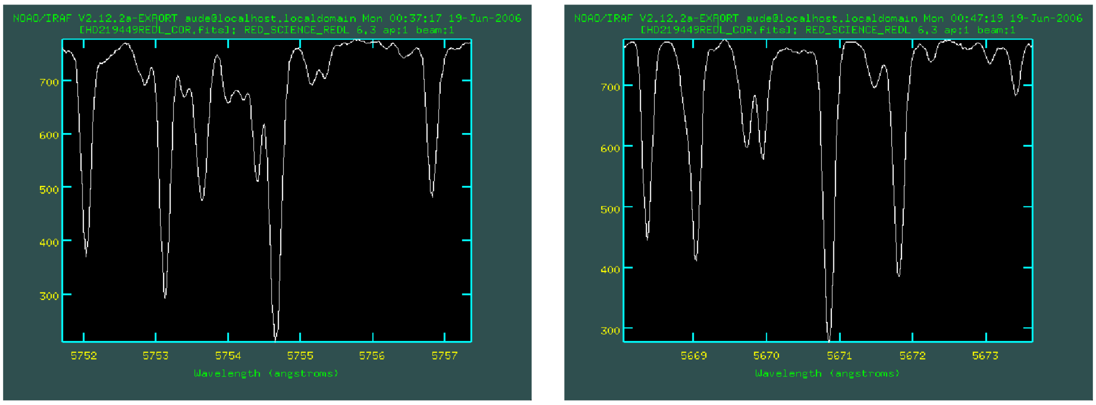
[1] Image Reduction and Analysis Facility



(a) The central line is bad blended

(b) Unblended and "well" blended lines

Figure 2.1: Example of bad, well and not blended lines

We have checked the equivalent width of the lines in a solar atlas, and have chosen lines with average strength, i.e equivalent width between 10 m$\AA$ and 200 m$\AA$.
The lines with equivalent width smaller than 200 m$\AA$ are more suitable for our calibration as they belongs to the linear part of the curve of growth of spectral lines, and therefore, are not distorted by saturation effects. Nevertheless, too weak lines (equivalent width lower than 10 m$\AA$) might not be found in some stars. This will affect the density of points in the calibration graph involving those lines, and therefore will reduce the statistic of the plot.

Applying all those criteria, we ended up with a list of 142 spectral lines, of which 78 unblended lines and 67 well blended lines. Thoses lines are from various chemical elements, such as VI, AlI, CaI, CoI, CrI, FeI, MgI, MnI, NaI, NiI, SI, ScII, SiI and TiI (I stands for neutral atom and II for one time ionized element). The line list resulting from this selection is appended to this report.

This line list of well or non blended lines, has been used as input to the IDL program computing the line ratios, as dicribed in the following subsection.

2.1.2 Selection of the ratios

The second step of my work was to build temperature sensitive line ratios using the lines selected as explained in the previous subsection.
Lines should not been randomly combined in ratios. For a line ratio to be a good temperature indicator, it has to fullfill some criteria listed here after.

To minimize the influance of the contiuum evaluation uncertainty on our ratios, we combined lines closed in wavelengths (Gray 1994). Indeed, the EW of lines closed in wavelength are affected the same way by the continuum. Thus, when computing the ratio, the contribution of the continuum will be canceled out. In their article Kovtykh at al. (2003) use a wavelength difference up to 70 $\AA$. They have tested this value and have found only small dispersion on the calibartion curve. As a first approach, we use the same value of wavelength difference in our calibration. Later, we will try to combine lines futher apart in wavelength ($\sim$ 100 $\AA$), as the continuum is well fitted we should not be affected differences in continuum.

To build ratios with high temperature sensibility, we combined lines with large difference in excitation potential. Indeed, lines of high or low excitation potential repond differently to the change in temperature. When the temperature varies the line strength of both lines do not respond the same way, leading to a greater change in the line ratio value.
D. Gray and L. Johanson (1991) use excitational potential difference of the 2 to 4 eV. In our work we are first trying with a vlaue of 3 eV.

Each ratio is made of lines from different chemical elements. Indeed if we combine lines from the same element, we migth be affected by other temperature dependent effects as the electronic population of energy levels can be interdependent.

We have also been carefull to combine elements having the same behaviour of [X/Fe] as a function of the metalicity [Fe/H].
We have classified the chimical elements in 5 categories, according to the variation of their abundance with regard to metallicity, using the graphs provided in G. Gilli et al (2004). FeI, MgI, SiI and TiI have been classified as constant in abundance with regards to metallicity. VI, AlI, NaI, NiI, ScII have been classified as constant-weak increasing in abundance with regards to metallicity. CaI has been classified as weakly decreasing, and CoI and MnI as strongly increasing in abundance with regards to metallicity.
We have only combined elements with same or similar behaviour with metallicity (e.g. weak decrease with constant, or strong increasing with weak increasing). We have avoided combination like strong increase and weak decrease, as such ratio will be sensitive to variation in metallicity among the sample of calibration stars.

2.1.3 IDl code : ratios.pro

To build ratios fullfilling all the creteria discribed in the previous subsection, I have written a short program in IDL[2]. This program, called ratios.pro, uses as input the line list discribed two subsections above. It combines the lines following all the criteria discribed in the previous subsection, and returns three output files: the list of ratios composed of well and non blended lines, the list of the lines appearing in those ratios, and the list of ratios only made of unblended lines. During the run, it also prints out on the IDL terminal, the number of ratios fullfilling the required conditions.

The calling sequence for this program is

```
IDL> .r ratios.pro
IDL> ratios, 70., 3., 1.5
```

The 70. stands for the maximum difference in wavelength (in $\AA$) between the two lines, 3. stands for the minimun difference in excitation potential (in eV), and 1.5 is a code number to tell the program to combine elements with same or similar abundance behaviour with regards to metallicity (if this value is set to 0.0, only the elements with same abundance behaviour will be combined). The value of those three parameters can be changed as required.

The code of this program is appended to this report.

Using $\Delta\lambda_{max}$ =70 $\AA$, ΔEP_{min} =3 eV and $\Delta behavirour = 1.5$, we ended up with 250 ratios made of 103 lines.
However, all those ratios do not give us good calibration curves. Indeed, some have high dispersion, bad sensitivity to temperature, or the spectral line(s) is(are) not found in the stellar spectra. This is what we are going to see in the following chapiter.

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[2] Interactive Data Language

Chapter 3

Stars and equivalent width

As shown in the previous chapiter, we have built a list of ratios with a good sensitivity to temperature, which would be interesting to use for temperature calibrations.
The calibration requires to measure those line ratios on many stars. The more stars is the best, as it will improve the precision of the calibration fit.

We have chosen to start with high resolution and high signal to noise spectra. Indeed, the goodness of the equivalent widths measurement depends on how well the blended lines can be separated, and on how well the noise contribution can be evaluated. In a high signal to noise spectra, the noise contribution to the continuum is less important, making the continuum determination more accurate. High resolution in a spectra will decrease the effect of the blend, as each line will be thiner.

3.1 The sample of stars

For the calibation we are using solar type stars with a temperature range of 4500 to 6500 K (F,G,K spectral type stars). Most of the stars used for the calibration are metal rich stars (see the star list appended to this report), i.e. they have metallicity greater than the solar metallicity. The spectral lines of metal rich stars are stronger, making easier their detection in the spectra.
The effective temperature of those stars have been taken from the 201 stellar sample of N. Santos et al.(2004, 2005), who have computed homogeneously the stellar parameters, among which the effective temperature, of those stars using stellar atmosphere models. The errors on those temperatures are of the order of 19 to $135 m\AA$.

We started by using only UVES[1] spectra because of the high resolution and the high signal to noise ratio of this spectrograph. UVES is a high resolution (up to 110000 in the red) optical spectrograph, mounted on the VLT[2] at La Silla in Chile. The VLT is a 8.2 m diameter telescope belonging to the ESO[3] community.

An echelle spectrograph takes multiple order spectra, allowing a wider coverage in wavelength. During the data reduction, the orders are extracted and combined into a single aperture spectrum.

3.1.1 Stellar sample already used

The calibration plots showed in this report are composed of 38 stars. Their spectra have been taken with UVES in 2004 (27 stars) and in 2001 (11 stars). The signal to noise ratios are of the order of 300 at lower wavelength and 800 at higher wavelength.

The star list is appended to this report.

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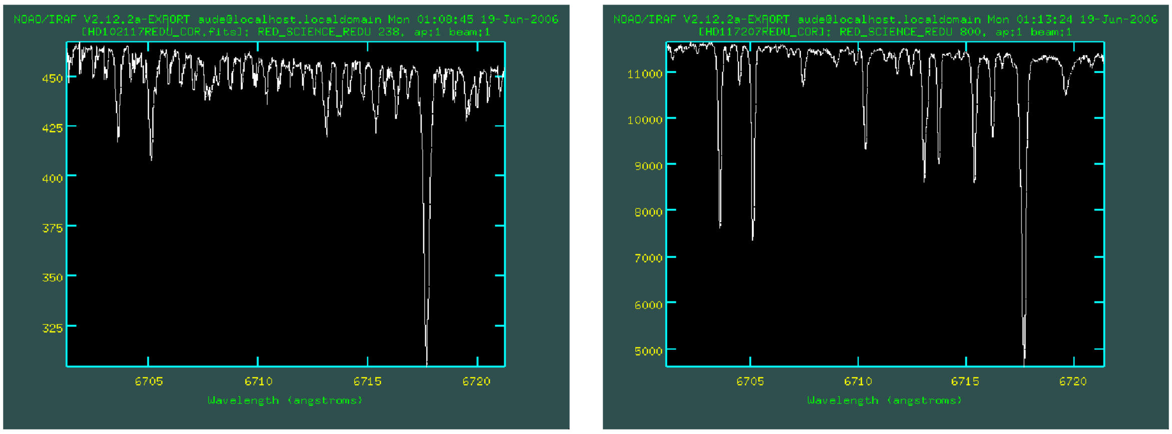
[1] Ultraviolet and Visible Echelle Spectrograph
[2] Very Large Telescope
[3] Europeen Southern Observatory

Those two series of spectra had already been reduced using a MIDAS[4] pipeline for UVES data for the spectra of 2004, and using IRAF for the spectra of 2001.
The spectra of 2001 appered as multiple aperture spectra. They have been combined in single aperture spectra using the SCOMBINE task of the noao.onedspec package of IRAF.

Lets explain briefly a problem encountered on the quality of the spectra used for the calibration. We had a star (HD102117) which spectra was harbouring strong fringing features starting around the H_α line (6563 $\AA$). This star presented a great dispersion on the calibration graphs, i.e the ratios calculated for this star were wrong. We could not correct it as explain in the following, and we had to remove this object from our list of stars.



(a) Spectrum with fringes

(b) Spectrum without fringes

Figure 3.1: Example of spectrum harbouring fringes

Fringes are due to interferences in the CCD. Why and when they occur is not yet well understood and above all they are quite difficult to correct.
So far, one way found to remove them is to use a fast rotating star. Indeed, this kind of stars have spectra with wide spectral lines. As the fringes are high frequency features, they will be easy to distinguish in this type of spectra. Fitting them and removing this fit from the data spectra can be a way to get rid of fringes. Nevetheless, this is not always obvious to achieve, and needs to identify a fast rotator visible during the obervation run. A. Ecuvillon and G. Israelian have tested this method.
Another way is to identified the spectra affected by fringes and to remove them before combining the different exposures. I have tested the spectrum with the selected exposure spectra, and there was no obvious improvement on the position of the star in the temperature versus ratio graphs. We think this can be because, to partially get rid of the fringes, we have combined only the less fringed spectra. Less exposure time means higher signal to noise ratio. Here comes another remark : the highest is the signal to noise ratio, the most difficult it is for DOASPEC to identify correctly the spectral lines. Indeed, DAOSPEC can mistake some noise features for lines.
Thus, when a spectrum turns out to harbour fringes, trying to remove them is a lot of unrewarding work. This easiest way is to remove them from the calibration.

3.1.2 More stars to be added soon

We have 14 more stars with UVES spectra, taken in service mode in 2005. They are well suitable for the first calibration, using only high resolution and high signal to noise spectra.

An other stage of my work was to reduced those data, using a modified version of the UVES pipeline of the package ESO MIDAS UVES. This version allows use a better control on the background fitting and on the cosmic ray filtering. There was 252 spectra in red to reduce. Each of them have been splited in two: the red low part and the red up range. Each of those parts had to be reducted separatly, timing by

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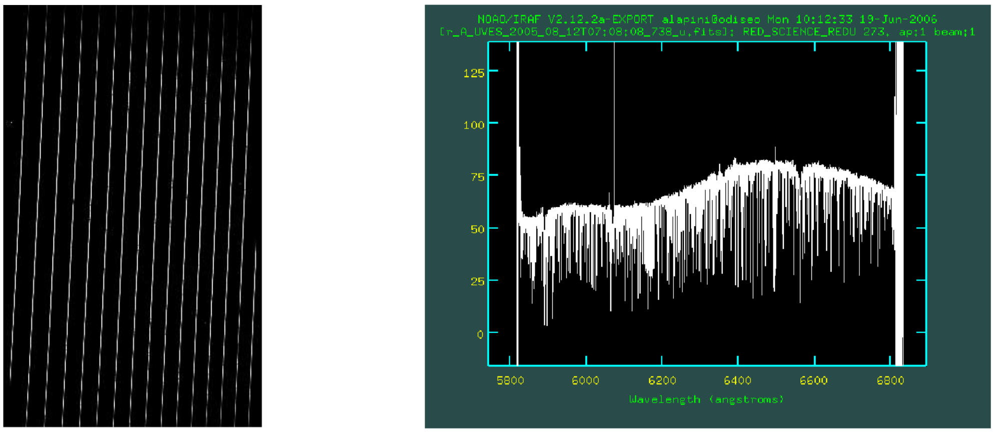
[4] Multivariate Interactive Data Analysis System

two the number of spectra to reduce.

Those stars have not yet been added in the calibration graphs appended to this report. Before measuring the equivalent width of the lines for those 14 stars, their spectra first need to be individualy corrected from radial velocity shifts (using the DOPCOR task of the onedspec package of IRAF), and combined star by star.
Combining many spectra of the same object increases the signal intensity without increasing the signal to noise ratio (as the noise has no spectral coherence). It is, therefore, more interessting to take many short exposures of the same object, even if it slows down the reduction process.



(a) Unreduced image of echelle spectrometer (b) Reduced and aperture combined spectrum

Figure 3.2: Example of reduced spectrum

3.2 Equivalent width measurement

To measure automatically the equivalent width of each line of our line list, for each star of our star list, we use a software called DAOSPEC.

3.2.1 DAOSPEC

DAOSPEC is a FORTRAN program written by P.B. Stetson at the Dominion Astrophysical Observatory (DAO) in Canada.
It detects spectral lines in a spectrum and measure their equivalent width in an automatic manner. It needs, in input, the spectrum (or many spectra from the same spectrograph) and two other files: daospec.opt and laboratory.dat.

The file daospec.opt contains the configuration parameters to run DAOSPEC. Those values can always be changed when DAOSPEC is running. However, the changes won't be saved and will be lost when closing the DAOSPEC session.
There are 16 differents configuration parameters :

1. or: the order of the continuum fitting has been set to 6. The largest is this value, the slowest will DAOSPEC run.

2. fw: the FWHM[5] is set to an intial estimate of the resolution of the spectrum(in unit of pixel). We used FWHM of 8 to 11, depending on the range in wavelength of the spectra. During its run DAOSPEC will addapt this parameter to the spectra. The closest is the first guess to the real value of FWHM, the fastest will be DAOSPEC.

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[5] Full Width at Half Maximum

3. sh and lo: the short and long wavelength limit of valid part of the spectrum. DAOSPEC will fit the continuum and measure the equivalent width of the spectral lines only on this range of wavelengths, even if it uses the whole spectra to compute the radial velocity displacement.
4. le and ri: the left and right edge of the window used to zoom on a spectral range, to monitor the progress of DAOSPEC while it is running.
5. re: the residual core flux (in %) corresponding to the percentage of continuum flux where lines saturate. We have set this value to 10 %.
6. mi and ma: the minimum and maximum radial velocity we are expected in the star. We have set these values to -4 and 4 respectively.
7. ve: the velocity limit (in σ), i.e. the maximum standard deviation from stellar radial velocity, before lines are discarded. We have set this value to 3 σ.
8. fi: this parameter (fix FWHM) is set to 0 to allow DAOSPEC to readjust the FWHM value, while computing. And is set to 1 to fix during the whole run the FWHM to the value defined in the fe parameter. We have set it to 0.
9. cr: this parameter (creat output) is set to 1 to creat continuum and residual output fits files, and to 0 otherwise.
10. wa: this parameter (watch progress) is set to 1 to ask DAOSPEC to draw pictures in the screen.
11. sm: this parameter (smallest equivalent width in m$\AA$) is set to the minimum equivalent width for a line to be reported in the star.daospec output file. We have set it to 2.
12. sc: this parameter scales the FWHM with lambda if set to 1, and uses single FWHM if set to 0.

The other input file, laboratory.dat, contains the list of the lines that will be used to measure the radial velocity displacement. The longest is the list, the smallest is the radial velocity displacement found by DAOSPEC in the spectrum. However, one has to be awared that the longest is the list the slowest runs DAOSPEC.

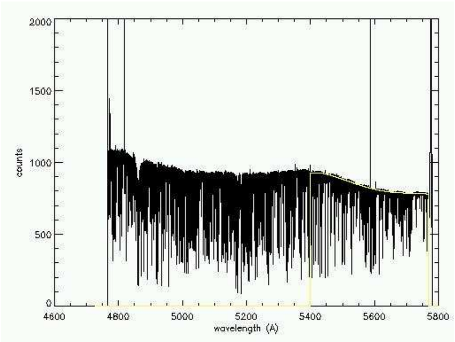
DAOSPEC can be launch on individual spectrum, or on many spectra at one time using a batch processing file. Only spectra with the same configuration (spectograph) can be launched at the same time. This is really useful mainly because of the gain of time in using such a procedure.

An example of doaspec.opt file is appended to this report, as well as a truncated version of the laboratory.dat file and an example of batch processing file.

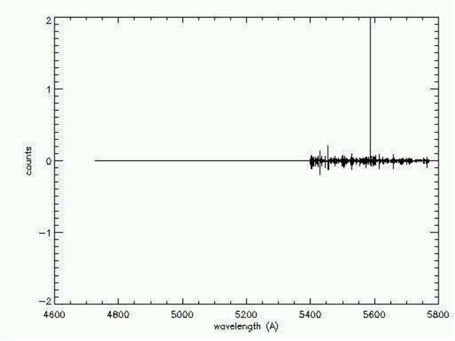
For each star, DAOSPEC produces an output file star.daospec containing the equivalent width of the spectral lines listed in the laboratory.dat file. When "Creat DAO Spectra (cr)" is set to 1, two other files are created: starC.fits is the .fits file of the continuum computed by DAOSPEC, and starR.fits is the .fits file of the residual.

DAOSPEC measures the continuum level, fits it and substracts it from the source spectra, and so on five times. Therefore, there is no need to normalise the spectra before running DAOSPEC. In IRAF, a spectrum can be normalized using the CONTINUUM routine in the noao.onedspec package. Moreover, there is no need to correct the spectra from radial velocity shift as DAOSPEC does it using the laboratory.dat file provided in input. In IRAF, a spectrum can be normalized using the DOPCOR task in the noao.onedspec package.

For more details on DAOSPEC, please refer to the "Cooking book" of DAOSPEC or visit the web pages :
http://cadcwww.hia.nrc.ca/stetson/daospec
http://stars.bo.astro.it/~GC/personal/epancino/projects/daospec.html



(a) Overplot of a non-normalized spectrum and of its continuum fit determinded by DAOSPEC, on the 5400-5800 $\mathring{A}$ wavelength range



(b) Residual of the normalization (difference between non-normalized and normalized spectrum) realized by DAOSPEC on the 5400-5800 $\mathring{A}$ wavelength range

Figure 3.3: Illustration of the continuum fitting realized by DAOSPEC

3.2.2 DAOSPEC vs IRAF

DAOSPEC is a great gain of time when measuring the equivalent width of the spectral lines. However, as it is an automated lines search program, we needed to test its accuracy. We have compared some of DAOSPEC equivalent width measurements with manual measurements using the SPLOT routine of IRAF. It turns out that the two methods agree within 5-10% percent errors, which is quite good considering the 10% uncertainties in measuring the continuum manually.
The errors on equivalent width measurements come mainly from the errors on the continuum fitting, but also from the capacity to extract the line contribution in the case of blended lines. Therefore, to check if DAOSPEC was dealing correctly with blended lines, we measured manually the equivalent of some well blended lines using the deblending command of the SPOLT task of IRAF. It appears that the difference between the two methods was in the error range (10%) of handmade measurements using IRAF. The errors on equivalent width measurement when using IRAF, come also mainly from the uncertainty on the handmade evaluation of the continuum level.

Therefore within 5-10%, DAOSPEC is able to measure correctly the equivalent width of spectral lines, including well blended lines.

DAOSPEC is known to underestimate the continuum level of around 3 $m\mathring{A}$ (see the manual "Cooking with DAOSPEC") in comparison with manual evaluations. In noisy spectra, this might be dued to the normalization method used by DAOSPEC. Indeed, DAOSPEC evaluates the continuum level, detecting the lines of the laboratory.dat file, substracting them from the spectrum, and so on five times. If the spectra is quite noisy, DAOSPEC can identify part of the noise as spectral lines and therefore substractes more than necessary. This results in a lower estimation of the continuum level.
S. Sousa et al. have worked on the comparison between DAOSPEC and IRAF, and have deduced a good agreement between the two method, especially in the red spectral range (Sousa et al. 2006, article should soon be published).

Chapter 4

Calibration curves

All the work, discribed in the previous chapters, had been done to build calibration curves of effective temperature against equivalent width line ratios. On one hand, we have built temperature sensitive line ratios, and on the other hand, we have measured the equivalent width of all the lines of the ratios for a sample of 38 stars. Now, lets see how we can combine the two to derive the effective temperature calibration curves.

4.1 IDL code: calibration.pro

To compute the line ratios for the 38 stars of our sample, I had to write an IDL program, called calibration.pro.
This program has three input files: the list of stars with their temperature, the list of DAOSPEC output file of each star (starname.daospec) containing all the equivalent width measurements, and the list of line ratios. It gives in output the calibration graphs of temperature vs ratio for each ratio with oveplotted 4th, 5th and 6th order polynomial fit. For each ratio, the best fit, i.e with the minimum standard deviation, will be the temperature calibration curve of this ratio.

The calling sequence for this program is

```
IDL> .r calibration.pro
IDL> calib
```

The code of this program is appended to this report.

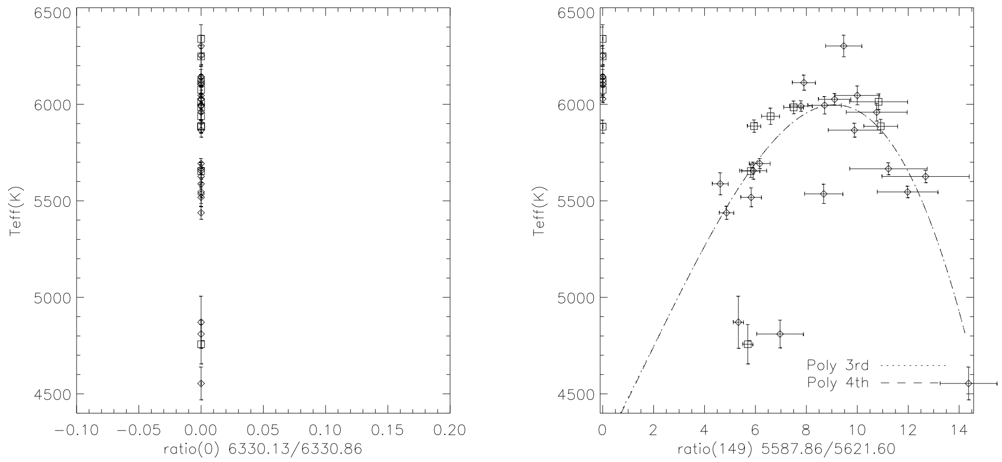
4.2 Calibration curves and fitting function

Several type of calibration curves are encountered among the 250 effective temperature versus line ratio graphs.
There are cases where at least one of the line of the ratio has not been found. When this occurs, the concerned stars are plotted with an equivalent width ratio of zero. There are other cases when no main trend of the temperature as a function of the ratio, stands out. We do not really know yet why some of the calibration graphs do not have a well defined relation between temperature and line ratio, while some others do. This could be caused by errors in the equivalent width measurement, for example when one line has not been identified correctly by DAOSPEC. This is something we are trying to improve as discussed in the following section. Those two first types of graphs are not of scientifical interest.
The third category is when the variation in temperature is well defined as a function of the line ratio. Those graphs have been fitted using a polynomial function of the 3^{rd} and 4^{th} order. The 12 best (small dispersion, good dynamics) calibration graphs, with the fits superimposed, can be find appended to this report.

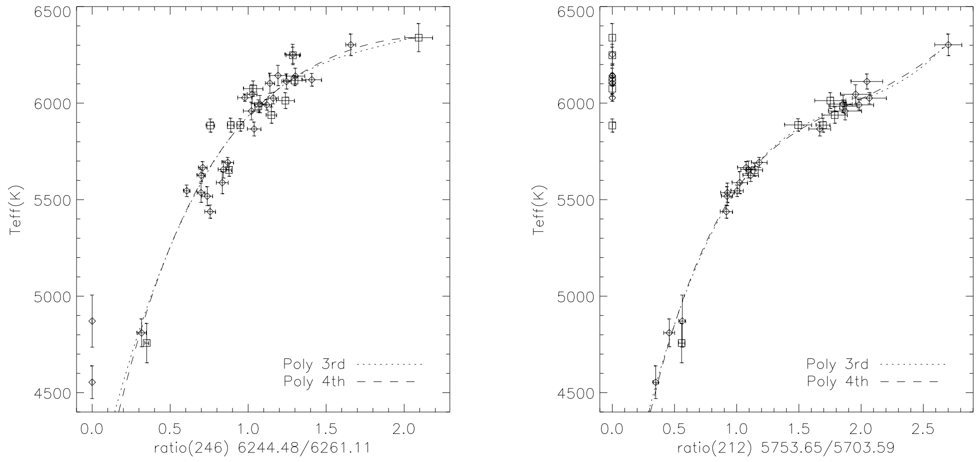
The fitting function used so far are very basic, and sometimes do not reflect correctly the tendancy of the observing effective temperature versus equivalent width line ratio. There are other simple functions one can use to fit the calibration, such as logaritmic, exponential or power law function, as will be seen in the following section.

For 117 line ratios, one or the two spectral lines were not found. All the stars then have a line ratio value of zero. Those graphs cannot be used for calibration.
Among the 133 remaining line ratios, 113 have well defined trend of temperature with equivalent width line ratio.
And among those 113, 12 have very small dispersion and have a very good sensitivity to temperature, i.e do not flatten in temperature at high value of the line ratio, or do not tend towards infinity for low value of the line ratio. For the remaining 101 line ratios, we will try to decrease the dispersion, as described in the following chapiter.

The 12 best calibration curves are appended to this report.



(a) Line(s) not found (b) High dispersion



(c) Low dispersion (d) Low dispersion, good dynamics

Figure 4.1: Example of the type of temperature vs ratio graphs encountered

Chapter 5

Futher work: improvement on the calibration curves accuracy

Best calibration can be achieved by improving the precision of the equivalent width measurement, by adding more stars to the plot, and by using more appropriate fitting function. Here after are some more details about those ways of improvements.

5.1 Equivalent width measurements

The calibration graphs are plots of effective temperature against equivalent width ratios. Therefore, the errors on the calibration curves depend on the errors on effective temperature measurements and on the ones of equivalent width measurements.

The errors on the temperature measurement are taken from the homogeneous stellar sample of N. Santos et al. (2004, 2005). The smallest error on effective temperature measured is 20 K but in average the errors are of the order of 50 K.

One way to improve the precision of our calibration curve is to decrease the errors on equivalent witdh measurements. As discribed in S. Sousa et al. (in press, 2006), DAOSPEC gives more precise values of the radial velocity shift when chosing small ranges of wavelengths for the continuum fitting and the line identification (parameter sh and lo of DAOSPEC). Our first attempt was to use the whole spectral range. We noticed an improvement on dispersions in the calibration graphs when using equivalent width ratios measured with a wavelength range of a third of the whole spectral range.
We are planning to reduce this wavelength range down to 100 $\AA$, i.e to run DAOSPEC 10 times for each stellar spectrum. This will take longer but will improve significantly the precision on the equivalent width measurement. Moreover, it can be done using a batch processing file containing the list of spectra to use and their associated configuration parameters.

The laboratory.dat file, containing the line list we want DAOSPEC to identify in the stellar spectrum, should have as many lines as possible as DAOSPEC needs a lot of comparison lines to evaluate correclty the radial velocity shift. If the radial velocity is not well measured, DAOSPEC might identifiy the lines in a wrong way, thus, inducing dispersion in our calibration graphs.
We are planning to add more comparison lines in the laboratory.dat file, especially for wavelengths between 5800 and 6800 $\AA$.
For now, we will not add more lines in the 4800 to 5800 $\AA$ range as we already have enough lines. DAOSPEC runs slower when dealing with a large input list of spectral lines. Therefore, there is a balance to find between the number of lines to ask DAOSPEC to identify and the time we are ready to spend on the equivalent width measurements.

5.2 Stellar sample

The precision of the calibration can be immproved by adding more calibration stars.

We have to add the remaining 14 stars taken in a service mode. Those stars have effective temperature between 4800 K and 6200 K.

We are also missing stars of effective temperature between 4500 K and 5500 K and above 6300 K. To fill those gaps, we are planning to add stellar spectra from other spectrometers, weighting the importance of using high quality (resolution, signal to noise ratio) spectra and the importance of having a large number of calibration stars for statistics and temperature range coverage.
In our spectral data base, we have stellar spectra from the FEROS[1] and the SARG[2] spectrometers. Those spectra are already reduced. We need to run DAOSPEC and add those stars in the calibration graphs.

5.3 Calibration fits

The aim of this project is to provide accurate calibration functions of effective temperature versus equivalent width line ratio.

So far, we have used polynomial fitting as first guess. However, logarithm, exponential or power law functions may provide even better fits to the data.
As each ratio has a different best fitting function and we are dealing with a large number of ratios, we decided to use a software which gives us a wide range of possible fitting functions to the data we provide, in order of goodness of the fit. This software, called TableCurve, is Windows based and is available on the web for free. TableCurve can return some very complicated functions and it is then up to us to chose the best and simplest fitting function (polynomial, logarithmic, exponantial or power law). Indeed, in physics, the simplest explaination is the best.

This investigation of the best fitting function is under process as it depends on the data provided. Those data are still under improvement as we need to get more accurate equivalent width measurements and to complete our stellar calibration sample.

5.4 Apply calibration

The first application should be on the Sun. Indeed, comparing the temperature derived from our calibration with the canonical Solar temperature, will allow us to fix the zero point of our temperature calibration scale.

Later, we will be able to use our calibration curves to measure temperature on solar-type stars. To evaluate the accuracy of our calibration, we will first work on a small sample of stars and compare the errors in temperature derived from our calibration curves with the ones found in the literature.

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[1] Fiber-fed Extended Range Optical Spectrometer, on the ESO 1.52m telescope in La Silla, Chile

[2] Spectrografe Alta Resolusions Galileo, on the Telescopio Nazional Galileo (TNG) in La Palma, Spain

Chapter 6

Conclusion

6.1 Conclusion on the effective temperature calibration using equivalent width ratios of spectral lines

We have selected a line list of 142 spectral lines (unblended, or blended with line cores well separated) from different chemical elements: VI, AlI, CaI, CoI, CrI, FeI, MgI, MnI, NaI, NiI, SI, ScII, SiI and TiI (I stands for neutral atom and II for one time ionized element).

Using this line list we have built 250 temperature sensitive line ratios. Each ratio is a combination of two lines from different chemical elements having the same abundance behaviour with metallicity. The combined lines are close in wavelength (seprations less than 70 $\mathring{A}$) and have a difference in excitation potential greater than 3 eV.

As calibrators, we have used UVES spectra of 38 solar-type stars with temperature between 4700 and 6400 K. We ran an automated spectral line search software, DAOSPEC, which calculates the equivalent widths of the lines provided in an input line list.

We have computed, for each of the 38 stars, the values of the 250 line ratios. Then, for each ratio, we have plotted a calibration graph of effective temperatures versus equivalent width ratio measurements. Finally, we have fitted those curves by 3^{rd} and 4^{th} order polynomial functions.
As a result of this work, we have obtained 113 good calibration curves of effective temperatures versus equivalent width ratio measurements. Among those 113 curves, 12 have very high accuracy.

There are various ways to improve the accuracy of our calibration curves, such as using more precised equivalent width measurements, larger sample of stars, and better fitting functions. Those improvements are under process and should be carried out by the end of August 2006.

Once those improvements are done, applying our calibration curves to the Sun will fix the zero point of our temperature calibration scale.
We shall apply our calibration to solar-type stars. Using 113 spectral line ratios, we are expecting to decrease the error bars on temperature by a factor of 10.

6.2 General conclusion on the work experience

This work experience has been a great opportunity for me, professionally, technically and socially speaking. I have learnt and done a lot, and still have some interesting work to complete.

Professionaly speaking, I have been working at the Instituto de Astrofisica de Canarias, an international center of research in astrophysics. I have observed two nights at the Telescopio Nazionale Galileo (TNG), at the Observatorio del Roque de Los Muchachos (ORM) in La Palma (Canary Islands, Spain), using the

SARG spectrometer. And, I have attended my first week of international conference "The Metal Rich Universe" taking place in June 2006 in La Palma.

Technically speaking, I have learnt spectral data reduction and analysis. I have developped my knowledge on IRAF tools and in IDL programming. I have learnt how to use efficiently DAOSPEC for equivalent width measurements, how to reduce UVES data using the ESO MIDAS UVES pipeline, how to use Table-Curve to find the best fitting functions to our calibration curves and how to observe with an automated professional telescope. I have had an overview on MOOG used to derive abundances. I have improved my communication skills in English and learnt Spanish.

And socially speaking, I have been working with new people, met new friends, and discovered the two great Islands of Tenerife and of La Palma.

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Chapter 7

Appendix

A Line ratios

A.1 List of spectral lines

Here after is the list of the spectral lines used in our effective temperature calibration.

Table 7.1: This table presents the list of spectral lines used in this project. The columns (1) and (2) have been taken for the VALD data base. The lines annotated "bl" are well blended. The ones annotated by an asterisk are not present in the 250 line ratios computed. In column (4), the K. stands for Kovtyukh, G. for Gilli(2006) and S. for Santos(2004). Continuation of this list on the following table

$\lambda(\AA)$	χ_l (1)	$\log gf$ (1)	$EW_\odot$ (m$\AA$)	(2)	(3)	Origin (4)	λ ($\AA$)	χ_l (1)	$\log gf$ (1)	$EW_\odot$ (m$\AA$)	(2)	(3)	Origin (4)
VI							AlI						
5670.85	1.08	−0.460	16			K.G.	6696.03	3.14	−1.570	33	bl	*	G.
5703.59	1.05	−0.211	26			K.	CaI						
5737.07	1.06	−0.770	11			G.	5512.98	2.93	−0.440	94		*	G.
6039.73	1.06	−0.650	11			K.	5590.12	2.52	−0.710	86	bl	*	G.
6090.21	1.08	−0.150	29			K.G.	5581.97	2.52	−0.650	91		*	G.
6081.44	1.05	−0.579	15	bl		K.	6166.44	2.52	−1.120	54		*	G.
6111.65	1.04	−0.715	12			K.	6169.05	2.52	−0.730	85	bl	*	G.
6135.36	1.05	−0.746	12	bl		K.	6169.56	2.52	−0.440	98	bl	*	G.
6216.35	0.28	−0.900	30	bl		G.	6449.82	2.52	−0.630	98	bl	*	G.
6243.11	0.30	−0.980	24	bl		K.	6455.60	2.52	−1.370	48		*	G.
6251.82	0.28	−1.340	12			K.							
NaI													
5688.22	2.10	−0.625	121	bl		G.							
6160.75	2.10	−1.316	44			G.							

Table 7.2: Continuation of table 7.1

$\lambda(\AA)$	χ_l (1)	$\log gf$ (1)	$EW_\odot$ (m$\AA$)	(2)	(3)	Origin (4)	λ ($\AA$)	χ_l (1)	$\log gf$ (1)	$EW_\odot$ (m$\AA$)	(2)	(3)	Origin (4)
CoI							FeI						
5301.04	1.71	−1.930	21	bl	*	G.	5247.06	0.09	−4.932	76	bl	*	S.
5342.70	4.02	0.574	29	bl	*	G.	5650.71	5.08	−0.960	34	bl		K.
5483.36	1.71	−1.220	42	bl	*	G.	5651.47	4.47	−2.000	16	bl		K.
5647.23	2.28	−1.580	11		*	G.	5662.52	4.17	−0.573	92	bl		K.
6093.14	1.74	−2.340	11		*	K.G.	5680.26	4.18	−2.580	10	bl		K.
6455.00	3.63	−0.280	11		*	G.	5691.51	4.30	−1.520	38	bl		K.
CrI							5696.10	4.54	−1.720	13	bl		K.
5665.56	4.92	−1.980	14	bl	*	G.	5701.54	2.55	−2.216	86			K.
5690.43	4.93	−1.790	19	bl	*	G.	5705.99	4.60	−0.530	74			K.
6330.13	0.94	−2.920	25			K.	5731.77	4.25	−1.300	59			K.
MgI							5753.12	4.26	−0.688	78	bl		K.
5711.09	4.34	−1.706	107			G.	5760.35	3.64	−2.490	18	bl	*	K.
6319.24	5.10	−2.179	39	bl		G.	5855.08	4.61	−1.529	23		*	S.
NiI						G.	5862.36	4.54	−0.058	87		*	K.
5413.68	3.85	−0.470	24			5956.70	0.85	−4.605	60		*	K.	
5578.72	1.67	−2.650	46			K.G.	5983.69	4.54	−1.878	68	bl		K.
5587.86	1.93	−2.380	49	bl		G.	5987.05	4.79	−0.556	68	bl		K.
5682.20	4.10	−0.390	52	bl		G.	6003.03	3.88	−1.120	86	bl	*	K.
5694.99	4.09	−0.600	44	bl		G.	6007.96	4.65	−0.966	59	bl		K.
5754.68	1.93	−2.330	73	bl		K.	6027.06	4.08	−1.180	66			S.
5847.00	1.68	−3.410	19		*	G.	6055.99	4.73	−0.460	73			K.S.
6007.31	1.67	−3.330	20			K.	6056.01	4.73	−0.498	73	bl		S.
6086.29	4.26	−0.440	43			K.G.	6062.89	2.17	−4.140	18	bl		K.
6108.12	1.67	−2.450	60			K.	6065.48	2.60	−1.530	115			K.
6130.14	4.26	−0.950	23	bl		G.	6078.50	4.79	−0.424	91			K.
6175.42	4.08	−0.559	36	bl		K.	6085.27	2.75	−3.095	40		*	K.
6176.81	4.08	−0.260	50			K.	6089.57	4.58	−3.112	32			K.
6186.74	4.10	−0.960	22			K.	6098.28	4.55	−1.880	16	bl		K.
6204.64	4.08	−1.100	16			K.	6102.18	4.83	−0.627	84	bl		K.
6327.60	1.67	−3.150	36			K.	6127.91	4.14	−1.399	48	bl		K.
6586.33	1.95	−2.810	35			K.	6151.62	2.17	−3.299	41			K.S.
6767.77	1.82	−2.170	83			K.	6157.73	4.07	−1.240	64	bl		S.
ScII							6159.38	4.61	−1.860	12			S.
5239.82	1.45	−0.760	55	bl	*	G.	6165.37	4.14	−1.503	43			S.
5318.36	1.36	−1.700	12		*	G.	6188.00	3.94	−1.631	50			S.
5526.82	1.77	0.150	76			G.	6200.32	2.60	−2.437	55			K.S.
6245.62	1.51	−1.040	30			G.	6213.43	2.22	−2.482	61			K.
SiI							6226.73	3.88	−2.066	31	bl		K.S.
5517.53	5.08	−2.384	14			K.	6229.23	2.84	−2.805	33		*	K.S.
5621.60	5.08	−2.500	11			K.	6232.65	3.65	−1.223	76			K.
5645.62	4.93	−2.140	35	bl		K.	6240.66	2.22	−3.233	40	bl		K.S.
5690.43	4.93	−1.790	53			K.G.	6246.32	3.60	−0.733	112			K.
5701.11	4.93	−2.020	40			K.G.	6252.55	2.40	−1.687	109			K.
5708.41	4.95	−1.470	77	bl		K.	6254.26	2.27	−2.443	115			K.
5753.65	5.61	−0.830	49	bl		K.	6265.13	2.17	−2.550	72	bl		K.S.
5772.15	5.08	−1.620	47			K.G.	6270.23	2.86	−2.583	56	bl	*	S.
6131.86	5.61	−1.140	27	bl		K.	6330.86	4.73	−1.740	32			K.
6142.49	5.61	−1.480	34			K.G.	6380.75	4.19	−1.321	52	bl		S.
6145.02	5.61	−1.480	38	bl		K.G.	6392.55	2.28	−3.932	19	bl		K.S.
6155.14	5.61	−0.750	72			K.G.	6419.98	4.73	−0.240	80	bl	*	K.
6243.81	5.61	−0.770	43	bl		K.	6591.33	4.59	−1.975	10	bl	*	S.
6244.48	5.61	−0.690	45			K.	6592.91	2.72	−1.473	12	bl		K.
6414.99	5.87	−1.100	45	bl		K.	6627.56	4.54	−1.680	24		*	K.S.
6583.71	5.95	−1.640	15			K.	6609.12	2.55	−2.692	76	bl		K.
6721.85	5.86	−1.090	55			K.G.	6653.84	4.15	−2.408	12	bl	*	S.
TiI							6677.99	2.69	−1.418	122	bl		K.
5490.15	1.46	−0.980	18	bl		K.G.	6725.39	4.10	−2.300	17		*	K.S.
6091.18	2.26	−0.460	14			K.G.	6726.68	4.61	−1.053	45		*	S.
6126.22	1.06	−1.410	20			K.G.	6733.18	4.64	−1.429	26		*	S.
6258.11	1.44	−0.440	42	bl		G.	6750.15	2.42	−2.621	75			K.S.
6261.11	1.43	−0.490	40			K.G.	6793.26	4.07	−2.326	10	bl	*	K.
							6806.85	2.72	−3.210	24		*	K.

A.2 List of line ratios

Among the 250 ratios computed by calibration.pro, there are three categories: the ratios suitable for the calibration (small dispersion), the ratios with high dispersion, and the ratios where at least one of the lines has not been found by DAOSPEC.

First, here after are the ratios with small dispersions, which can be used for the temperature calibration. We will need to understand the cause of the dispersion and try to correct it to obtain more precised calibration curves.

Table 7.3: This table presents the 12 best ratios obtained during this project. Those ratios have small dispersions and a large dynamical range in temperature. The "bl" key word indicates well blended lines. Δbe is the difference indicates abundance behaviour with metallicity of the chemical elements used in the ratio (0.0 stands for identical behaviours, and 1.5 for similar behaviours)

ratio		λ ($\AA$)		λ ($\AA$)		$\Delta\lambda$ ($\AA$)	ΔEP (eV)	Δbe
6	FeI	5650.71	VI	5703.59	bl -	52.88	4.034	1.5
15	FeI	5691.51	VI	5703.59	bl -	12.08	3.250	1.5
25	FeI	5731.77	VI	5703.59		28.18	3.205	1.5
27	FeI	5753.12	VI	5703.59	bl -	49.53	3.209	1.5
42	FeI	6056.01	NiI	6108.12	bl -	52.11	3.054	1.5
152	NiI	5682.20	VI	5703.59	bl -	21.39	3.049	0.0
155	NiI	5694.99	VI	5703.59	bl -	8.60	3.039	0.0
202	SiI	5645.62	VI	5703.59	bl -	57.97	3.879	1.5
204	SiI	5690.43	VI	5703.59		13.16	3.879	1.5
207	SiI	5701.11	VI	5703.59		2.48	3.879	1.5
212	SiI	5753.65	VI	5703.59	bl -	50.06	4.565	1.5
217	SiI	6131.86	TiI	6126.22	bl -	5.64	4.549	0.0

Table 7.4: This second table of line ratios presents the 101 remaining ratios with small dispersions. They have a shorter dynamical ranges, as their curves of temperature vs ratio flatten or tend rapidly towards infinity at high temperatures. Same comments on "bl" and Δbe as in 7.3. Continuation of the list on the following table.

ratio		λ ($\AA$)		λ ($\AA$)		$\Delta\lambda$ ($\AA$)	ΔEP (eV)	Δbe
3	FeI	5619.60	VI	5670.85		51.25	3.305	1.5
5	FeI	5650.71	VI	5670.85	bl -	20.14	4.004	1.5
7	FeI	5651.47	VI	5670.85	bl -	19.38	3.392	1.5
9	FeI	5662.52	VI	5670.85	bl -	8.33	3.097	1.5
10	FeI	5662.52	VI	5703.59	bl -	41.07	3.127	1.5
13	FeI	5680.26	VI	5737.07	bl -	56.81	3.126	1.5
14	FeI	5691.51	VI	5670.85	bl -	20.66	3.220	1.5
16	FeI	5691.51	VI	5737.07	bl -	45.56	3.241	1.5
17	FeI	5696.10	VI	5670.85	bl -	25.25	3.467	1.5
19	FeI	5696.10	VI	5737.07	bl -	40.97	3.488	1.5
21	FeI	5705.99	VI	5670.85		35.14	3.526	1.5
24	FeI	5731.77	VI	5670.85		60.92	3.175	1.5
26	FeI	5731.77	VI	5737.07		5.30	3.196	1.5
28	FeI	5753.12	VI	5737.07	bl -	16.05	3.200	1.5
46	FeI	6056.01	VI	6111.65	bl -	55.64	3.687	1.5
49	FeI	6078.50	NiI	6108.12		29.62	3.119	1.5
50	FeI	6078.50	TiI	6126.22		47.72	3.728	0.0
54	FeI	6078.50	VI	6111.65		33.15	3.752	1.5
56	FeI	6089.57	TiI	6126.22		36.65	3.513	0.0
60	FeI	6089.57	VI	6111.65		22.08	3.537	1.5
66	FeI	6098.28	VI	6111.65	bl -	13.37	3.515	1.5

Table 7.5: Continuation of table 7.4

ratio		λ ($\AA$)		λ ($\AA$)		$\Delta\lambda$ ($\AA$)	ΔEP (eV)	Δbe
68	FeI	6102.18	NiI	6108.12	bl -	5.94	3.159	1.5
69	FeI	6102.18	TiI	6126.22	bl -	24.04	3.768	0.0
73	FeI	6102.18	VI	6111.65	bl -	9.47	3.792	1.5
75	FeI	6127.91	TiI	6126.22	bl -	1.69	3.076	0.0
78	FeI	6127.91	VI	6111.65	bl -	16.26	3.100	1.5
82	FeI	6151.62	SiI	6145.02	- bl	6.60	3.440	0.0
83	FeI	6151.62	SiI	6155.14		3.52	3.443	0.0
90	FeI	6159.38	VI	6111.65		47.73	3.567	1.5
93	FeI	6165.37	TiI	6126.22		39.15	3.073	0.0
94	FeI	6165.37	VI	6111.65		53.72	3.097	1.5
99	FeI	6188.00	VI	6251.82		63.82	3.653	1.5
103	FeI	6200.32	SiI	6155.14		45.18	3.011	0.0
110	FeI	6226.73	VI	6216.35	bl - bl	10.38	3.600	1.5
112	FeI	6226.73	VI	6251.82	bl -	25.09	3.593	1.5
129	FeI	6392.55	SiI	6414.99	bl - bl	22.44	3.591	0.0
134	MgI	5711.09	VI	5670.85		40.24	3.265	1.5
135	MgI	5711.09	VI	5703.59		7.50	3.295	1.5
140	MgI	6319.24	VI	6251.82	bl -	67.42	4.821	1.5
144	NaI	6160.75	SiI	6145.02	- bl	15.73	3.512	1.5
145	NaI	6160.75	SiI	6155.14		5.61	3.515	1.5
151	NiI	5682.20	VI	5670.85	bl -	11.35	3.019	0.0
153	NiI	5682.20	VI	5737.07	bl -	54.87	3.040	0.0
154	NiI	5694.99	VI	5670.85	bl -	24.14	3.009	0.0
156	NiI	5694.99	VI	5737.07	bl -	42.08	3.030	0.0
157	NiI	5754.68	SiI	5708.41	bl - bl	46.27	3.019	1.5
160	NiI	6086.29	TiI	6126.22		39.93	3.199	1.5
164	NiI	6086.29	VI	6111.65		25.36	3.223	0.0
168	NiI	6108.12	SiI	6145.02	- bl	36.90	3.940	1.5
169	NiI	6108.12	SiI	6155.14		47.02	3.943	1.5
170	NiI	6130.14	TiI	6126.22	bl -	3.92	3.193	1.5
173	NiI	6130.14	VI	6111.65	bl -	18.49	3.217	0.0
180	NiI	6176.81	TiI	6126.22		50.59	3.021	1.5
181	NiI	6176.81	VI	6111.65		65.16	3.045	0.0
185	NiI	6186.74	TiI	6126.22		60.52	3.038	1.5
187	NiI	6186.74	VI	6216.35	- bl	29.61	3.825	0.0
200	SiI	5621.60	VI	5670.85		49.25	4.001	1.5
201	SiI	5645.62	VI	5670.85	bl -	25.23	3.849	1.5
203	SiI	5690.43	VI	5670.85		19.58	3.849	1.5
205	SiI	5690.43	VI	5737.07		46.64	3.870	1.5
206	SiI	5701.11	VI	5670.85		30.26	3.849	1.5
208	SiI	5701.11	VI	5737.07		35.96	3.870	1.5
209	SiI	5708.41	VI	5670.85	bl -	37.56	3.873	1.5
210	SiI	5708.41	VI	5703.59	bl -	4.82	3.903	1.5
211	SiI	5708.41	VI	5737.07	bl -	28.66	3.894	1.5
213	SiI	5753.65	VI	5737.07	bl -	16.58	4.556	1.5
220	SiI	6131.86	VI	6111.65	bl -	20.21	4.573	1.5
229	SiI	6145.02	TiI	6126.22	bl -	18.80	4.549	0.0
232	SiI	6145.02	VI	6111.65	bl -	33.37	4.573	1.5
235	SiI	6155.14	TiI	6126.22		28.92	4.552	0.0
237	SiI	6155.14	VI	6111.65		43.49	4.576	1.5
239	SiI	6155.14	VI	6216.35	- bl	61.21	5.339	1.5
245	SiI	6244.48	TiI	6258.11	- bl	13.63	4.176	0.0
246	SiI	6244.48	TiI	6261.11		16.63	4.186	0.0
249	SiI	6244.48	VI	6251.82		7.34	5.329	1.5

Secondly, here after are the line ratios with high dispersions. We will need to understand what causes does dispersions.

Table 7.6: This table lists the line ratios with high dispersion. Same comments on "bl" and Δbe as in 7.3.

ratio		λ ($\AA$)		λ ($\AA$)		$\Delta\lambda$ ($\AA$)	ΔEP (eV)	Δbe
4	FeI	5650.71	NiI	5587.86	bl - bl	62.85	3.155	1.5
8	FeI	5651.47	VI	5703.59	bl -	52.12	3.422	1.5
11	FeI	5680.26	VI	5670.85	bl -	9.41	3.105	1.5
12	FeI	5680.26	VI	5703.59	bl -	23.33	3.135	1.5
18	FeI	5696.10	VI	5703.59	bl -	7.49	3.497	1.5
20	FeI	5701.54	SiI	5753.65	- bl	52.11	3.057	0.0
22	FeI	5705.99	VI	5703.59		2.40	3.556	1.5
23	FeI	5705.99	VI	5737.07		31.08	3.547	1.5
62	FeI	6098.28	TiI	6126.22	bl -	27.94	3.491	0.0
80	FeI	6151.62	SiI	6131.86	- bl	19.76	3.440	0.0
86	FeI	6157.73	VI	6135.36	bl - bl	22.37	3.019	1.5
92	FeI	6159.38	VI	6216.35	- bl	56.97	4.330	1.5
96	FeI	6165.37	VI	6216.35	- bl	50.98	3.860	1.5
97	FeI	6188.00	VI	6216.35	- bl	28.35	3.660	1.5
98	FeI	6188.00	VI	6243.11	- bl	55.11	3.639	1.5
100	FeI	6200.32	SiI	6131.86	- bl	68.46	3.008	0.0
102	FeI	6200.32	SiI	6145.02	- bl	55.30	3.008	0.0
105	FeI	6200.32	SiI	6244.48		44.16	3.008	0.0
111	FeI	6226.73	VI	6243.11	bl - bl	16.38	3.579	1.5
113	FeI	6232.65	VI	6216.35	- bl	16.30	3.374	1.5
114	FeI	6232.65	VI	6243.11	- bl	10.46	3.353	1.5
115	FeI	6232.65	VI	6251.82		19.17	3.367	1.5
130	FeI	6592.91	SiI	6583.71	bl -	9.20	3.227	0.0
131	FeI	6609.12	SiI	6583.71	bl -	25.41	3.395	0.0
132	FeI	6677.99	SiI	6721.85	bl -	43.86	3.171	0.0
133	FeI	6750.15	SiI	6721.85		28.30	3.439	0.0
136	MgI	5711.09	VI	5737.07		25.98	3.286	1.5
138	MgI	6319.24	TiI	6258.11	bl - bl	61.13	3.668	0.0
139	MgI	6319.24	TiI	6261.11	bl -	58.13	3.678	0.0
141	NaI	5688.22	SiI	5753.65	bl - bl	65.43	3.512	1.5
142	NaI	6160.75	SiI	6131.86	- bl	28.89	3.512	1.5
146	NiI	5578.72	SiI	5517.53		61.19	3.406	1.5
147	NiI	5578.72	SiI	5621.60		42.88	3.406	1.5
148	NiI	5578.72	SiI	5645.62	- bl	66.90	3.254	1.5
149	NiI	5587.86	SiI	5621.60	bl -	33.74	3.152	1.5
150	NiI	5587.86	SiI	5645.62	bl - bl	57.76	3.000	1.5
158	NiI	5754.68	SiI	5753.65	bl - bl	1.03	3.681	1.5
183	NiI	6176.81	VI	6216.35	- bl	39.54	3.808	0.0
184	NiI	6176.81	VI	6243.11	- bl	66.30	3.787	0.0
188	NiI	6186.74	VI	6243.11	- bl	56.37	3.804	0.0
189	NiI	6186.74	VI	6251.82		65.08	3.818	0.0
196	ScII	5526.82	SiI	5517.53		9.29	3.312	1.5
199	SiI	5517.53	TiI	5490.15	- bl	27.38	3.622	0.0
247	SiI	6244.48	VI	6216.35	- bl	28.13	5.336	1.5
248	SiI	6244.48	VI	6243.11	- bl	1.37	5.315	1.5

And finally, here after are the ratios for which at least one of the lines has not been found by DAOSPEC. This results is line ratios of value zero. We will need to understand why DAOSPEC has not found those spectral lines and see if it is because of blends, line strength, or for any another reason.

Table 7.7: This table lists the 117 line ratios we have not been able to calculate. Same comments on "bl" and Δbe as in 7.3.

ratio		λ ($\AA$)		λ ($\AA$)		$\Delta\lambda$ ($\AA$)	ΔEP (eV)	Δbe
0	CrI	6330.13	FeI	6330.86		0.730	3.792	1.5
1	CrI	6330.13	FeI	6380.75	- bl	50.62	3.249	1.5
2	CrI	6330.13	MgI	6319.24	- bl	10.89	4.167	1.5
29	FeI	5983.69	VI	6039.73	bl -	56.04	3.485	1.5
30	FeI	5987.05	NiI	6007.31	bl -	20.26	3.119	1.5
31	FeI	5987.05	VI	6039.73	bl -	52.68	3.731	1.5
32	FeI	6007.96	VI	6039.73	bl -	31.77	3.588	1.5
33	FeI	6027.06	VI	6039.73		12.67	3.016	1.5
34	FeI	6027.06	VI	6081.44	- bl	54.38	3.029	1.5
35	FeI	6055.99	NiI	6007.31		48.68	3.057	1.5
36	FeI	6055.99	NiI	6108.12		52.13	3.057	1.5
37	FeI	6055.99	VI	6039.73		16.26	3.669	1.5
38	FeI	6055.99	VI	6090.21		34.22	3.652	1.5
39	FeI	6055.99	VI	6081.44	- bl	25.45	3.682	1.5
40	FeI	6055.99	VI	6111.65		55.66	3.690	1.5
41	FeI	6056.01	NiI	6007.31	bl -	48.70	3.054	1.5
43	FeI	6056.01	VI	6039.73	bl -	16.28	3.666	1.5
44	FeI	6056.01	VI	6090.21	bl -	34.20	3.649	1.5
45	FeI	6056.01	VI	6081.44	bl - bl	25.43	3.679	1.5
47	FeI	6062.89	SiI	6131.86	bl - bl	68.97	3.440	0.0
48	FeI	6065.48	SiI	6131.86	- bl	66.38	3.008	0.0
51	FeI	6078.50	VI	6039.73		38.77	3.731	1.5
52	FeI	6078.50	VI	6090.21		11.71	3.714	1.5
53	FeI	6078.50	VI	6081.44	- bl	2.94	3.744	1.5
55	FeI	6078.50	VI	6135.36	- bl	56.86	3.744	1.5
57	FeI	6089.57	VI	6039.73		49.84	3.516	1.5
58	FeI	6089.57	VI	6090.21		0.64	3.499	1.5
59	FeI	6089.57	VI	6081.44	- bl	8.13	3.529	1.5
61	FeI	6089.57	VI	6135.36	- bl	45.79	3.529	1.5
63	FeI	6098.28	VI	6039.73	bl -	58.55	3.494	1.5
64	FeI	6098.28	VI	6090.21	bl -	8.07	3.477	1.5
65	FeI	6098.28	VI	6081.44	bl - bl	16.84	3.507	1.5
67	FeI	6098.28	VI	6135.36	bl - bl	37.08	3.507	1.5
70	FeI	6102.18	VI	6039.73	bl -	62.45	3.771	1.5
71	FeI	6102.18	VI	6090.21	bl -	11.97	3.754	1.5
72	FeI	6102.18	VI	6081.44	bl - bl	20.74	3.784	1.5
74	FeI	6102.18	VI	6135.36	bl - bl	33.18	3.784	1.5
76	FeI	6127.91	VI	6090.21	bl -	37.70	3.062	1.5
77	FeI	6127.91	VI	6081.44	bl - bl	46.47	3.092	1.5
79	FeI	6127.91	VI	6135.36	bl - bl	7.45	3.092	1.5
81	FeI	6151.62	SiI	6142.49		9.13	3.443	0.0
84	FeI	6157.73	TiI	6126.22	bl -	31.51	3.003	0.0
85	FeI	6157.73	VI	6111.65	bl -	46.08	3.027	1.5
87	FeI	6157.73	VI	6216.35	bl - bl	58.62	3.790	1.5
88	FeI	6159.38	TiI	6126.22		33.16	3.543	0.0
89	FeI	6159.38	VI	6090.21		69.17	3.529	1.5
91	FeI	6159.38	VI	6135.36	- bl	24.02	3.559	1.5
95	FeI	6165.37	VI	6135.36	- bl	30.01	3.089	1.5
101	FeI	6200.32	SiI	6142.49		57.83	3.011	0.0
104	FeI	6200.32	SiI	6243.81	- bl	43.49	3.008	0.0
106	FeI	6213.43	SiI	6145.02	- bl	68.41	3.393	0.0
107	FeI	6213.43	SiI	6155.14		58.29	3.396	0.0
108	FeI	6213.43	SiI	6243.81	- bl	30.38	3.393	0.0
109	FeI	6213.43	SiI	6244.48		31.05	3.393	0.0
116	FeI	6240.66	SiI	6243.81	bl - bl	3.15	3.393	0.0
117	FeI	6240.66	SiI	6244.48	bl -	3.82	3.393	0.0
118	FeI	6246.32	VI	6216.35	- bl	29.97	3.322	1.5
119	FeI	6246.32	VI	6243.11	- bl	3.21	3.301	1.5
120	FeI	6246.32	VI	6251.82		5.50	3.315	1.5
121	FeI	6252.55	SiI	6243.81	- bl	8.74	3.212	0.0
122	FeI	6252.55	SiI	6244.48		8.07	3.212	0.0
123	FeI	6254.26	SiI	6243.81	- bl	10.45	3.337	0.0
124	FeI	6254.26	SiI	6244.48		9.78	3.337	0.0
125	FeI	6265.13	SiI	6243.81	bl - bl	21.32	3.440	0.0
126	FeI	6265.13	SiI	6244.48	bl -	20.65	3.440	0.0

Table 7.8: Continuation of table 7.7

ratio		λ ($\AA$)		λ ($\AA$)		$\Delta\lambda$ ($\AA$)	ΔEP (eV)	Δbe
127	FeI	6330.86	NiI	6327.60		3.26	3.057	1.5
128	FeI	6330.86	TiI	6261.11		69.75	3.303	0.0
137	MgI	6319.24	NiI	6327.60	bl -	8.36	3.432	1.5
143	NaI	6160.75	SiI	6142.49		18.26	3.515	1.5
159	NiI	5754.68	SiI	5772.15	bl -	17.47	3.147	1.5
161	NiI	6086.29	VI	6039.73		46.56	3.202	0.0
162	NiI	6086.29	VI	6090.21		3.92	3.185	0.0
163	NiI	6086.29	VI	6081.44	- bl	4.85	3.215	0.0
165	NiI	6086.29	VI	6135.36	- bl	49.07	3.215	0.0
167	NiI	6108.12	SiI	6142.49		34.37	3.943	1.5
171	NiI	6130.14	VI	6090.21	bl -	39.93	3.179	0.0
172	NiI	6130.14	VI	6081.44	bl - bl	48.70	3.209	0.0
174	NiI	6130.14	VI	6135.36	bl - bl	5.22	3.209	0.0
175	NiI	6175.42	TiI	6126.22	bl -	49.20	3.022	1.5
176	NiI	6175.42	VI	6111.65	bl -	63.77	3.046	0.0
177	NiI	6175.42	VI	6135.36	bl - bl	40.06	3.038	0.0
178	NiI	6175.42	VI	6216.35	bl - bl	40.93	3.809	0.0
179	NiI	6175.42	VI	6243.11	bl - bl	67.69	3.788	0.0
182	NiI	6176.81	VI	6135.36	- bl	41.45	3.037	0.0
186	NiI	6186.74	VI	6135.36	- bl	51.38	3.054	0.0
190	NiI	6204.64	VI	6135.36	- bl	69.28	3.037	0.0
191	NiI	6204.64	VI	6216.35	- bl	11.71	3.808	0.0
192	NiI	6204.64	VI	6243.11	- bl	38.47	3.787	0.0
193	NiI	6204.64	VI	6251.82		47.18	3.801	0.0
194	NiI	6586.33	SiI	6583.71		2.62	4.003	1.5
195	NiI	6767.77	SiI	6721.85		45.92	4.037	1.5
197	ScII	6245.62	SiI	6243.81	- bl	1.81	4.106	1.5
198	ScII	6245.62	SiI	6244.48		1.14	4.106	1.5
166	NiI	6108.12	SiI	6131.86	- bl	23.74	3.940	1.5
214	SiI	5772.15	VI	5703.59		68.56	4.031	1.5
215	SiI	5772.15	VI	5737.07		35.08	4.022	1.5
216	SiI	6131.86	TiI	6091.18	bl -	40.68	3.349	0.0
218	SiI	6131.86	VI	6090.21	bl -	41.65	4.535	1.5
219	SiI	6131.86	VI	6081.44	bl - bl	50.42	4.565	1.5
221	SiI	6131.86	VI	6135.36	bl - bl	3.50	4.565	1.5
222	SiI	6142.49	TiI	6091.18		51.31	3.352	0.0
223	SiI	6142.49	TiI	6126.22		16.27	4.552	0.0
224	SiI	6142.49	VI	6090.21		52.28	4.538	1.5
225	SiI	6142.49	VI	6081.44	- bl	61.05	4.568	1.5
226	SiI	6142.49	VI	6111.65		30.84	4.576	1.5
227	SiI	6142.49	VI	6135.36	- bl	7.13	4.568	1.5
228	SiI	6145.02	TiI	6091.18	bl -	53.84	3.349	0.0
230	SiI	6145.02	VI	6090.21	bl -	54.81	4.535	1.5
231	SiI	6145.02	VI	6081.44	bl - bl	63.58	4.565	1.5
233	SiI	6145.02	VI	6135.36	bl - bl	9.66	4.565	1.5
234	SiI	6155.14	TiI	6091.18		63.96	3.352	0.0
236	SiI	6155.14	VI	6090.21		64.93	4.538	1.5
238	SiI	6155.14	VI	6135.36	- bl	19.78	4.568	1.5
240	SiI	6243.81	TiI	6258.11	bl - bl	14.30	4.176	0.0
241	SiI	6243.81	TiI	6261.11	bl -	17.30	4.186	0.0
242	SiI	6243.81	VI	6216.35	bl - bl	27.46	5.336	1.5
243	SiI	6243.81	VI	6243.11	bl - bl	0.70	5.315	1.5
244	SiI	6243.81	VI	6251.82	bl -	8.01	5.329	1.5

B Calibration stars

Table 7.9: This table presents the 38 solar type stars used to build our calibration graphs. The spectra of those stars were taken in 2001 and 2004 on the UVES spectrometer of the VLT.

star	Teff (K)	[Fe/H]	Obs. date	star	Teff (K)	[Fe/H]	Obs. date
HD142	6302 ± 56	0.14 ± 0.07	2004	HD73256	5518 ± 49	0.26 ± 0.06	2004
HD1237	5536 ± 50	0.12 ± 0.06	2004	HD73526	5699 ± 49	0.27 ± 0.06	2004
HD4208	5626 ± 32	−0.24 ± 0.04	2004	HD74156	6112 ± 39	0.16 ± 0.05	2004
HD7570	6140 ± 41	0.18 ± 0.05	2001	HD75289	6143 ± 53	0.28 ± 0.07	2001
HD17051	6252 ± 53	0.26 ± 0.06	2001	HD82943	6028 ± 19	0.29 ± 0.02	2001
HD19994	6121 ± 33	0.19 ± 0.05	2001	HD88133	5438 ± 34	0.33 ± 0.05	2004
HD23079	5959 ± 46	−0.11 ± 0.06	2004	HD99492	4810 ± 72	0.26 ± 0.07	2004
HD28185	5656 ± 44	0.22 ± 0.05	2004	HD106252	5866 ± 36	−0.03 ± 0.05	2004
HD30177	5588 ± 57	0.39 ± 0.06	2004	HD108147	6248 ± 42	0.20 ± 0.05	2001
HD33636	6046 ± 49	−0.08 ± 0.06	2004	HD114386	4834 ± 77	−0.04 ± 0.07	2004
HD37124	5546 ± 30	−0.38 ± 0.04	2004	HD114762	5884 ± 34	−0.25 ± 0.05	2001
HD39091	5991 ± 27	0.10 ± 0.04	2004	HD117207	5654 ± 33	0.23 ± 0.05	2004
HD47536	4554 ± 85	−0.54 ± 0.12	2004	HD120136	6339 ± 73	0.23 ± 0.07	2001
HD50554	6026 ± 30	0.01 ± 0.04	2004	HD121504	6075 ± 40	0.16 ± 0.05	2001
HD52265	6103 ± 52	0.25 ± 0.06	2001	HD209458	6117 ± 26	0.02 ± 0.03	2001
HD59686	4871 ± 135	0.28 ± 0.18	2004	HD213240	5984 ± 33	0.17 ± 0.05	2004
HD65216	5666 ± 31	−0.12 ± 0.04	2004	HD216435	5938 ± 42	0.24 ± 0.05	2004
HD70642	5693 ± 26	0.18 ± 0.04	2004	HD216437	5887 ± 32	0.25 ± 0.04	2004
HD72659	5995 ± 45	0.03 ± 0.06	2004	HD219449	4757 ± 102	0.05 ± 0.14	2004

Table 7.10: This second table presents the list of the 14 stars observed in service mode (2005) with the UVES spectrometer of the VLT. Their spectra will soon be used to complete the stellar sample in our calibration.

star	Teff (K)	[Fe/H]	Obs. date
HD2039	5976 ± 51	0.32 ± 0.06	2005
HD4203	5636 ± 40	0.40 ± 0.05	2005
HD41004	5242 ± 57	0.16 ± 0.07	2005
HD76700	5737 ± 34	0.41 ± 0.05	2005
HD114729	5886 ± 36	−0.25 ± 0.05	2005
HD117618	6013 ± 41	0.06 ± 0.06	2005
HD128311	4835 ± 72	0.03 ± 0.07	2005
HD154857	5610 ± 27	−0.23 ± 0.04	2005
HD177830	4804 ± 77	0.33 ± 0.09	2005
HD190228	5327 ± 35	−0.27 ± 0.06	2005
HD190360	5584 ± 36	0.24 ± 0.05	2005
HD208487	6141 ± 29	0.06 ± 0.04	2005
HD216770	5423 ± 41	0.26 ± 0.04	2005
HD330075	5017 ± 53	0.08 ± 0.06	2005

C DAOSPEC input files

C.1 daospec.opt

Here is an example of a daospec.opt file with the typical parameter values used. Note that the value of parameter changes for each spectral range and for each spectrograph.//

```
or=6      order for continuum fitting
fw=11.0   intial estimate of the resolution of the spectrum(unit=pixel)
sh=6470   short wavelength limit of valid part of the spectrum
lo=6820   long wavelength limit of valid part of the spectrum
le=6525.  left edge of the window (zoom on a spectral range, monitoring)
ri=6550.  right edge of the window (zoom on a spectral range, monitoring)
re = 10   residual core flux (% of contiuum flux where lines saturate)
mi = -4   minimum radiale velocity (within, star has instantaneous geocentric rv)
ma = 4    maximum radiale velocity (within, star has instantaneous geocentric rv)
ve=3      velocity limit (max std dev from stellar rv b4 line discarded)
fi=0.     fix FWHM (0 : DAO find the best FWHM, 1: FWHM fixed by user)
cr=1.     create output (continuum and residuals) spectra (1: yes, 0: no)
wa=1      watch progress (1: draw picture on the monitor, 0: don't)
sm=2      smallest equivalent width (min EW b4 line not reported)
sc=1.     scale FWHM with lambda (1: yes, 0: single FWHM used)
```

C.2 Truncated laboratory.dat file

Here is a truncated version of the laboratory.dat file used with DAOSPEC.
The structure of the line comments is important, as the comments are reported in the *.daospec output file, next to the corresponding line. The IDL program, calibration.pro, reads this file with a defined format to extracte the columns of the file. Therefore, to allow a correct lecture and extraction of data, the structure of laboratory.dat should be respected.
In the following, the lines with comments are the ones of our line list, used to build our line ratios. The other lines, taken in VALD and NIST atomic database, have been added to have a uniform and dense distribution of reference lines over the wavelength range of our spectra. Indeed, as seen in the main part of this report, the dispersion of radial velocity found by DAOSEPC decereases when the number of reference lines in laboratory.dat increases.

```
Input line list for DAOSPEC

Rq on EP & log(gf)
- values taken from VALD database

Rq on bl column
- unblended line = 0
- well blended   = 1
- bad blended    = 2

Rq on be column : behaviour of [X/Fe] with regards to [Fe/H] (Gilli2006)
- 0.0 = [X/Fe] bw constant and weak increasing with [Fe/H]
- 1.5 = [X/Fe] constant with [Fe/H]
- 3.0 = [X/Fe] bw constant and weak decreasing with [Fe/H]
- 4.5 = [X/Fe] weak decreasing with [Fe/H]
- 8.0 = [X/Fe] strong increasing with [Fe/H]

Rq on orig column
- K. = from Kovtyukh's lines
- G. = from Gilli(2006)'s lines
- M. = from Santos's FeI lines
```

```
Elements' atomic number (.0 = neurtal, .1= 1 time ionized):
- VI  = 23.0
- AlI = 13.0
- Ba2 = 56.1
- CaI = 20.0
- CoI = 27.0
- CrI = 24.0
- Eu2 = 63.1
- FeI = 26.0
- Fe2 = 26.1
- La2 = 57.1
- MgI = 12.0
- MnI = 25.0
- NaI = 11.0
- NiI = 28.0
- SI  = 16.0
- Sc2 = 21.1
- SiI = 14.0
- TiI = 22.0
- Ti2 = 22.1

wavelgt  el   EP    log(gf) bl  be  orig
     (eV)
##

4807.52 23.0
4827.46 23.0
.
.
.
5626.02 23.0 1.0430  -1.240  1  0.0  K.
5670.85 23.0 1.0810  -0.420  0  0.0  K.
5703.59 23.0 1.0640  -0.650  0  0.0  K.
5737.07 23.0 1.06    -0.770  0  0.0  G.
6039.74 23.0 1.0640  -0.650  0  0.0  K.
6081.45 23.0 1.0510  -0.579  1  0.0  K.
6090.22 23.0 1.0810  -0.062  0  0.0  K.
6111.65 23.0 1.0430  -0.715  0  0.0  K.
6119.53 23.0 1.0640  -0.320  1  0.0  K.
6135.37 23.0 1.0510  -0.746  1  0.0  K.
6150.15 23.0
6199.19 23.0 0.2870  -1.300  1  0.0  K.
6216.35 23.0 0.28    -0.900  1  0.0  G.
6233.20 23.0
6243.11 23.0 0.3010  -0.980  1  0.0  K.
6251.82 23.0 0.2870  -1.340  0  0.0  K.
6285.17 23.0
6452.32 23.0
.
.
.
5512.98 20.0 2.93    -0.440  0  4.5  G.
5581.97 20.0 2.52    -0.650  0  4.5  G.
5590.12 20.0 2.52    -0.710  1  4.5  G.
5857.45 20.0
6102.72 20.0
6122.23 20.0
```

```
6156.03 20.0
6161.30 20.0
6162.17 20.0
6166.44 20.0 2.52    -1.120  0  4.5  G.
6169.05 20.0 2.52    -0.730  1  4.5  G.
6169.56 20.0 2.52    -0.440  1  4.5  G.
6439.08 20.0
6449.82 20.0 2.52    -0.630  1  4.5  G.
6455.60 20.0 2.52    -1.370  0  4.5  G.
.
.
.
6091.17 22.0 2.2670  -0.423  0  1.5  K.
6126.22 22.0 1.0670  -1.425  0  1.5  K.
6220.50 22.0
6258.11 22.0 1.44    -0.440  1  1.5  G.
6258.71 22.0
6261.11 22.0 1.5.43  -0.490  0  1.5  K.G.
6303.76 22.0
6312.24 22.0
.
.
.
6606.95 22.1
6680.13 22.1
```

C.3 Batch processing

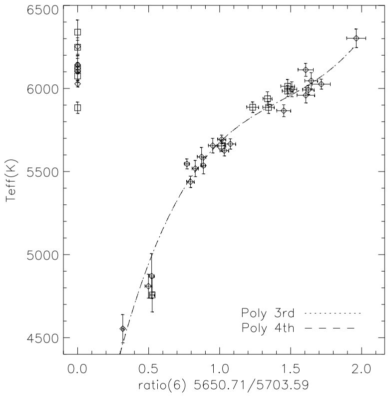
Here is an example of batch file. The calling sequence for this batch, in a linux terminal, is "¿ batch" and all the lines (except the ones starting by # which are comment lines) are executed.

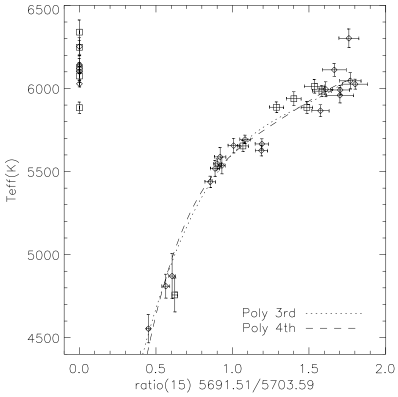
```
# !/bin/csh                    # Tell the system where is csh
#                              # Comment
rm HD*.daospec                 # Remove previous output
daospec <<DONE>!  logfile      # Run DAOSPEC and save log
WA=0                           # Mandatory for batch processing

HD102117REDU_COR.fits          # Work on  spectrum
HD106252REDU_COR.fits          # Work on  spectrum
.
.
.
HD88133REDU_COR.fits           # Work on  spectrum
HD99492REDU_COR.fits           # Work on  spectrum

DONE                           # End of input list for DAOSPEC
```

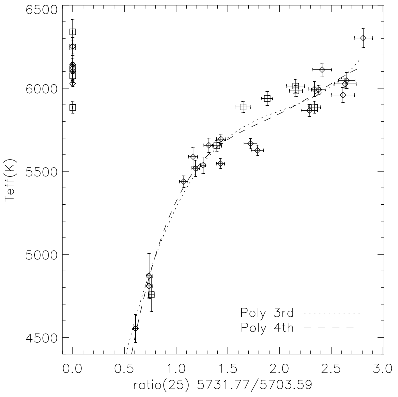
D The calibration plots

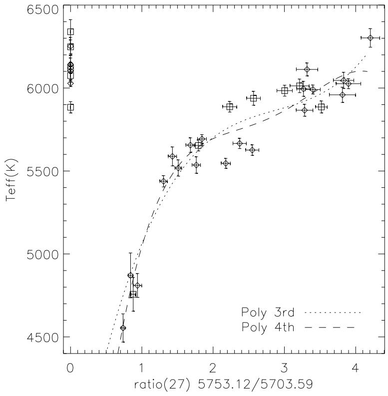
D.1 The plots

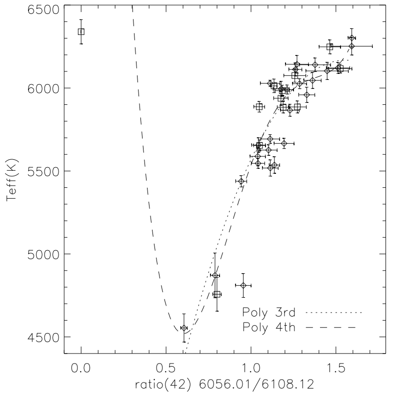
Here after are the 12 best calibration curves we have obtained, with small dispersions and a large dynamical range (i.e a small variation of the ratio leads to a large variation of the temperature). The data have been fitted by polynomial function of the 3rd and of the 4th order. As we can see from the plots, a 3rd order polynomial function is sufficient to fit those data.

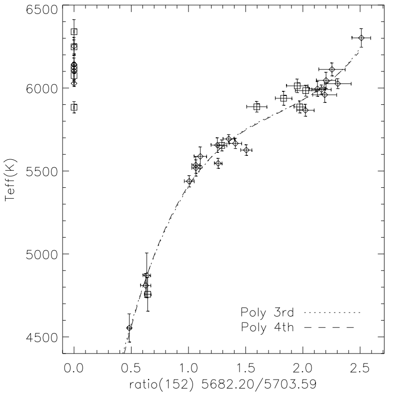


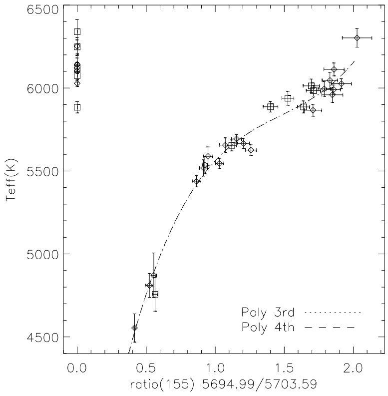


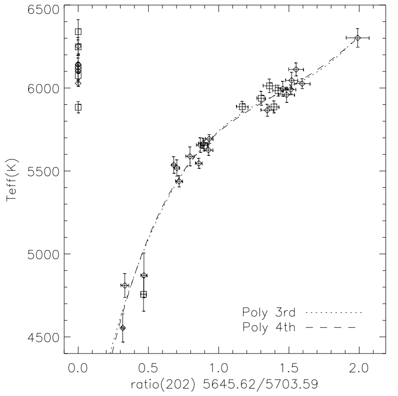


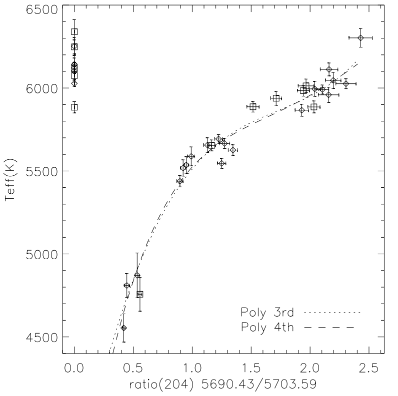


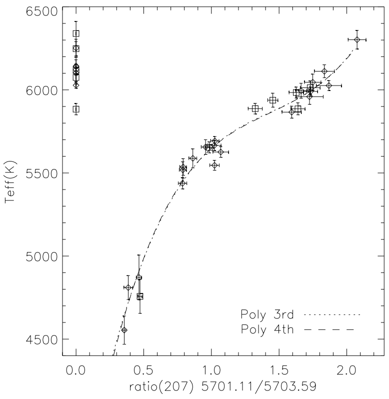


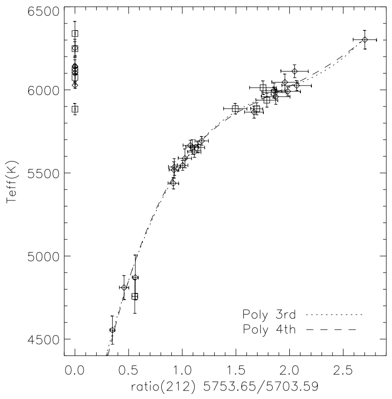


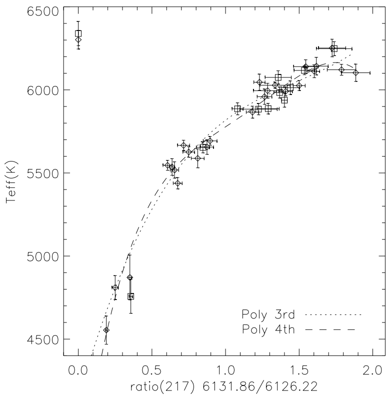












D.2 3rd order polynomial fitting function

A 3rd order polynimial function has for equation:

$$y = C_0 + C_1 x + C_2 x^2 + C_3 x^3 \tag{7.1}$$

In our calibration curves, "y" is the effective temperature and "x" is the line ratio. Here after are the values of the 4 coefficients found for our 12 best calibration curves.

Table 7.11: This table gives the coefficients of the 3rd order polynomial functions fitting the 12 best calibration curves derived from our data.

ratio	C_0	C_1	C_2	C_3
6	3250 ± 170	4690 ± 460	-2950 ± 401	68 ± 110
15	2440 ± 270	6240 ± 730	3990 ± 630	920 ± 170
25	2700 ± 200	4240 ± 380	-1980 ± 220	330 ± 40
27	3430 ± 150	2300 ± 200	-760 ± 81	90 ± 10
42	1150 ± 730	6780 ± 1940	-2480 ± 1700	130 ± 490
152	2980 ± 180	4190 ± 390	-2170 ± 270	410 ± 60
155	2900 ± 200	5200 ± 530	-3230 ± 440	730 ± 120
202	3590 ± 130	4170 ± 360	-2620 ± 320	610 ± 90
204	3530 ± 140	3460 ± 320	-1820 ± 230	350 ± 50
207	3400 ± 140	4380 ± 370	-2790 ± 320	650 ± 90
212	3570 ± 120	3280 ± 250	-1580 ± 165	270 ± 30
217	4140 ± 100	3090 ± 290	-1820 ± 270	410 ± 70

E IDL programs

E.1 Ratios.pro

```
;*********************************************************************
;
;   Build line ratios
;
;criteria :
;- closed wavelengths
;- high difference in excitation potential
;- pair of different chimical elements
;- pair of chimical elements having the same behaviour of
;[X/Fe] in function of [Fe/H]
;
;*********************************************************************

;calling sequences :
;Windows
;IDL>.r E:\Stage_IAC\IDL\pro\ratios.pro
;Linux
;IDL>.r /scratch/Stage_IAC/idl/pro/ratios.pro
;
;IDL> ratios, 70., 3., 1.5
;
;*********************************************************************

pro ratios, dlamb_max, dEP_min, dbe_max

    ;dLamb_max in Angstrom
    ;EP_min in eV
    ;dbe_max = 0.0 (only same behaviour),
    ;          1.5 (similar behaviour)

    path = 'E:\Stage_IAC\IDL\IDL_aspid_07_06\'        ;path Windows
    ;path = '/scratch/Stage_IAC/idl/IDL_aspid_07_06/'   ;path Linux

    Infile = 'InLineList.txt'
    FMT  = 'F,F,F,F,I,F,A5'

    ;-----------------------------------
    ;read input file (= DAOSPEC's output)
    ;-----------------------------------
    print, " "
    print, " 1. Read input file "

    ; Windows
    readcol, path + Infile, $
          wlab, el, EP, lgf, bl, be, orig, $
          FORMAT=FMT, SKIPLINE=2, /SILENT
    ; Linux
    ;readcol, Infile, $
    ;      wlab, el, EP, lgf, bl, be, orig, $
    ;      FORMAT=FMT, SKIPLINE=2, /SILENT

    print, " "
```

```
;-----------------------------------
;Select ratios
;-----------------------------------
print, " 2. Start Select ratios"

N = n_elements(wlab)
print, "# of lines (wlab)                                    ", N

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;calcul dLamb and select dlamb < dlamb_max;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
print, " 2.1. Calcul dLamb and select dlamb < dlamb_max"

wlab1_todos = 0.
wlab2_todos = 0.
EP1_todos   = 0.
EP2_todos   = 0.
el1_todos   = 0.
el2_todos   = 0.
be1_todos   = 0.
be2_todos   = 0.
bl1_todos   = 0.
bl2_todos   = 0.
for i=0, (N-1) do begin
;for i=0, 4 do begin
for j=i+1, (N-1) do begin
;for j=i+1, 4 do begin
    wlab1_todos = [wlab1_todos,wlab(i)]
    wlab2_todos = [wlab2_todos,wlab(j)]
    EP1_todos   = [EP1_todos,EP(i)]
    EP2_todos   = [EP2_todos,EP(j)]
    el1_todos   = [el1_todos,el(i)]
    el2_todos   = [el2_todos,el(j)]
    be1_todos   = [be1_todos,be(i)]
    be2_todos   = [be2_todos,be(j)]
    bl1_todos   = [bl1_todos,bl(i)]
    bl2_todos   = [bl2_todos,bl(j)]
endfor
endfor
wlab1_todos = wlab1_todos(1:*)
wlab2_todos = wlab2_todos(1:*)
EP1_todos   = EP1_todos(1:*)
EP2_todos   = EP2_todos(1:*)
el1_todos   = el1_todos(1:*)
el2_todos   = el2_todos(1:*)
be1_todos   = be1_todos(1:*)
be2_todos   = be2_todos(1:*)
bl1_todos   = bl1_todos(1:*)
bl2_todos   = bl2_todos(1:*)

dlamb_todos = wlab1_todos-wlab2_todos

sel_dlamb = where(abs(dlamb_todos) le dlamb_max, dimsel_dlamb)

print, "# of combi with dLamb < dLamb_max                    ", $
        dimsel_dlamb
```

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;calcul dEP and select dEP > dEP_min among the dlamb < dlamb_max;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
print, " 2.2. Calcul dEP and select dEP > dEP_min, among dlamb < dlamb_max"

N2 = dimsel_dlamb
wlab1_dlamb = wlab1_todos(sel_dlamb)
wlab2_dlamb = wlab2_todos(sel_dlamb)
dlamb_dlamb = dlamb_todos(sel_dlamb)
EP1_dlamb   = EP1_todos(sel_dlamb)
EP2_dlamb   = EP2_todos(sel_dlamb)
el1_dlamb   = el1_todos(sel_dlamb)
el2_dlamb   = el2_todos(sel_dlamb)
be1_dlamb   = be1_todos(sel_dlamb)
be2_dlamb   = be2_todos(sel_dlamb)
bl1_dlamb   = bl1_todos(sel_dlamb)
bl2_dlamb   = bl2_todos(sel_dlamb)

dEP_dlamb         = EP2_dlamb-EP1_dlamb
dlamb_dlamb       = wlab2_dlamb-wlab1_dlamb

sel_dEP_dlamb = where(abs(dEP_dlamb) ge dEP_min, dimsel_dEP_dlamb)

print, "# of combi with dLamb < dLamb_max & dEP > dEP_min     ",$
        dimsel_dEP_dlamb

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;condition on elements and behaviour with metallicity ;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

;............................................
; Select ratios made with different elements
;............................................
print, " 2.3. Select ratios made of different elements"

N3 = dimsel_dEP_dlamb
el1_dEP_dlamb   = el1_dlamb(sel_dEP_dlamb)
el2_dEP_dlamb   = el2_dlamb(sel_dEP_dlamb)
be1_dEP_dlamb   = be1_dlamb(sel_dEP_dlamb)
be2_dEP_dlamb   = be2_dlamb(sel_dEP_dlamb)
bl1_dEP_dlamb   = bl1_dlamb(sel_dEP_dlamb)
bl2_dEP_dlamb   = bl2_dlamb(sel_dEP_dlamb)
wlab1_dEP_dlamb = wlab1_dlamb(sel_dEP_dlamb)
wlab2_dEP_dlamb = wlab2_dlamb(sel_dEP_dlamb)
EP1_dEP_dlamb   = EP1_dlamb(sel_dEP_dlamb)
EP2_dEP_dlamb   = EP2_dlamb(sel_dEP_dlamb)

dEP_dEP_dlamb   = dEP_dlamb(sel_dEP_dlamb)
dlamb_dEP_dlamb = dlamb_dlamb(sel_dEP_dlamb)

sel_el_dEP_dlamb = where(el1_dEP_dlamb ne el2_dEP_dlamb, dimsel_el_dEP_dlamb)

print, "# of combi (dLamb<dLamb_max, dEP>dEP_min & el1 ne el2)",$
        dimsel_el_dEP_dlamb

;............................................
```

```
; Select ratios made with different elements
;.........................................
print, " 2.4. Select ratios made of elements with same behaviour"

N4 = dimsel_el_dEP_dlamb
be1_el_dEP_dlamb   = be1_dEP_dlamb(sel_el_dEP_dlamb)
be2_el_dEP_dlamb   = be2_dEP_dlamb(sel_el_dEP_dlamb)
bl1_el_dEP_dlamb   = bl1_dEP_dlamb(sel_el_dEP_dlamb)
bl2_el_dEP_dlamb   = bl2_dEP_dlamb(sel_el_dEP_dlamb)
el1_el_dEP_dlamb   = el1_dEP_dlamb(sel_el_dEP_dlamb)
el2_el_dEP_dlamb   = el2_dEP_dlamb(sel_el_dEP_dlamb)
wlab1_el_dEP_dlamb = wlab1_dEP_dlamb(sel_el_dEP_dlamb)
wlab2_el_dEP_dlamb = wlab2_dEP_dlamb(sel_el_dEP_dlamb)
EP1_el_dEP_dlamb   = EP1_dEP_dlamb(sel_el_dEP_dlamb)
EP2_el_dEP_dlamb   = EP2_dEP_dlamb(sel_el_dEP_dlamb)

dEP_el_dEP_dlamb   = dEP_dEP_dlamb(sel_el_dEP_dlamb)
dlamb_el_dEP_dlamb = dlamb_dEP_dlamb(sel_el_dEP_dlamb)
dbe_el_dEP_dlamb   = be2_el_dEP_dlamb-be1_el_dEP_dlamb

sel_dbe_el_dEP_dlamb  = where(abs(dbe_el_dEP_dlamb) le dbe_max,dimsel_dbe_el_dEP_dlamb)

print, "# of combi fulfilling conditions on dLamb, dEP, el, be",$
        dimsel_dbe_el_dEP_dlamb

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;condition on blending                           ;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
print, " 2.5. Select ratios with unblended line"


N5 = dimsel_dbe_el_dEP_dlamb
be1_dbe_el_dEP_dlamb   = be1_el_dEP_dlamb(sel_dbe_el_dEP_dlamb)
be2_dbe_el_dEP_dlamb   = be2_el_dEP_dlamb(sel_dbe_el_dEP_dlamb)
bl1_dbe_el_dEP_dlamb   = bl1_el_dEP_dlamb(sel_dbe_el_dEP_dlamb)
bl2_dbe_el_dEP_dlamb   = bl2_el_dEP_dlamb(sel_dbe_el_dEP_dlamb)
el1_dbe_el_dEP_dlamb   = el1_el_dEP_dlamb(sel_dbe_el_dEP_dlamb)
el2_dbe_el_dEP_dlamb   = el2_el_dEP_dlamb(sel_dbe_el_dEP_dlamb)
wlab1_dbe_el_dEP_dlamb = wlab1_el_dEP_dlamb(sel_dbe_el_dEP_dlamb)
wlab2_dbe_el_dEP_dlamb = wlab2_el_dEP_dlamb(sel_dbe_el_dEP_dlamb)
EP1_dbe_el_dEP_dlamb   = EP1_el_dEP_dlamb(sel_dbe_el_dEP_dlamb)
EP2_dbe_el_dEP_dlamb   = EP2_el_dEP_dlamb(sel_dbe_el_dEP_dlamb)

sel_u_dbe_el_dEP_dlamb = where((bl1_dbe_el_dEP_dlamb+bl2_dbe_el_dEP_dlamb) eq 0.0, $
                                dimsel_u_dbe_el_dEP_dlamb)

print, "# of combi fulfilling dLamb, dEP, el, be, unbl        ",$
        dimsel_u_dbe_el_dEP_dlamb

N6 = dimsel_u_dbe_el_dEP_dlamb
el1_u_dbe_el_dEP_dlamb   = el1_dbe_el_dEP_dlamb(sel_u_dbe_el_dEP_dlamb)
el2_u_dbe_el_dEP_dlamb   = el2_dbe_el_dEP_dlamb(sel_u_dbe_el_dEP_dlamb)
wlab1_u_dbe_el_dEP_dlamb = wlab1_dbe_el_dEP_dlamb(sel_u_dbe_el_dEP_dlamb)
wlab2_u_dbe_el_dEP_dlamb = wlab2_dbe_el_dEP_dlamb(sel_u_dbe_el_dEP_dlamb)
bl1_u_dbe_el_dEP_dlamb   = bl1_dbe_el_dEP_dlamb(sel_u_dbe_el_dEP_dlamb)
bl2_u_dbe_el_dEP_dlamb   = bl2_dbe_el_dEP_dlamb(sel_u_dbe_el_dEP_dlamb)
be1_u_dbe_el_dEP_dlamb   = be1_dbe_el_dEP_dlamb(sel_u_dbe_el_dEP_dlamb)
```

```
be2_u_dbe_el_dEP_dlamb   = be2_dbe_el_dEP_dlamb(sel_u_dbe_el_dEP_dlamb)
EP1_u_dbe_el_dEP_dlamb   = EP1_dbe_el_dEP_dlamb(sel_u_dbe_el_dEP_dlamb)
EP2_u_dbe_el_dEP_dlamb   = EP2_dbe_el_dEP_dlamb(sel_u_dbe_el_dEP_dlamb)

print, " "

;--------------------------------------------------
;preparing the list of the lines used in the ratios
;--------------------------------------------------

wlab_dbe_el_dEP_dlamb = wlab1_dbe_el_dEP_dlamb
el_dbe_el_dEP_dlamb = el1_dbe_el_dEP_dlamb
EP_dbe_el_dEP_dlamb = EP1_dbe_el_dEP_dlamb
bl_dbe_el_dEP_dlamb = bl1_dbe_el_dEP_dlamb
be_dbe_el_dEP_dlamb = be1_dbe_el_dEP_dlamb

for i=0, N5-1 do begin
    wlab_dbe_el_dEP_dlamb = [wlab_dbe_el_dEP_dlamb,wlab2_dbe_el_dEP_dlamb(i)]
    el_dbe_el_dEP_dlamb   = [el_dbe_el_dEP_dlamb,el2_dbe_el_dEP_dlamb(i)]
    EP_dbe_el_dEP_dlamb   = [EP_dbe_el_dEP_dlamb,EP2_dbe_el_dEP_dlamb(i)]
    bl_dbe_el_dEP_dlamb   = [bl_dbe_el_dEP_dlamb,bl2_dbe_el_dEP_dlamb(i)]
    be_dbe_el_dEP_dlamb   = [be_dbe_el_dEP_dlamb,be2_dbe_el_dEP_dlamb(i)]
endfor

N_temp = n_elements(wlab_dbe_el_dEP_dlamb)

sel_temp = intarr(N_temp)
for i=0, N_temp-1 do begin
    sel_temp(i)=i
endfor

wlab_dbe_el_dEP_dlamb_list = 0.
el_dbe_el_dEP_dlamb_list = 0.
EP_dbe_el_dEP_dlamb_list = 0.
bl_dbe_el_dEP_dlamb_list = 0.
be_dbe_el_dEP_dlamb_list = 0.
dimsel_temp = 1.

while dimsel_temp gt 0. do begin
    wlab_dbe_el_dEP_dlamb = wlab_dbe_el_dEP_dlamb(sel_temp)
    el_dbe_el_dEP_dlamb   = el_dbe_el_dEP_dlamb(sel_temp)
    EP_dbe_el_dEP_dlamb   = EP_dbe_el_dEP_dlamb(sel_temp)
    bl_dbe_el_dEP_dlamb   = bl_dbe_el_dEP_dlamb(sel_temp)
    be_dbe_el_dEP_dlamb   = be_dbe_el_dEP_dlamb(sel_temp)

    wlab_dbe_el_dEP_dlamb_list=[wlab_dbe_el_dEP_dlamb_list,wlab_dbe_el_dEP_dlamb(0)]
    el_dbe_el_dEP_dlamb_list  =[el_dbe_el_dEP_dlamb_list,el_dbe_el_dEP_dlamb(0)]
    EP_dbe_el_dEP_dlamb_list  =[EP_dbe_el_dEP_dlamb_list,EP_dbe_el_dEP_dlamb(0)]
    bl_dbe_el_dEP_dlamb_list  =[bl_dbe_el_dEP_dlamb_list,bl_dbe_el_dEP_dlamb(0)]
    be_dbe_el_dEP_dlamb_list  =[be_dbe_el_dEP_dlamb_list,be_dbe_el_dEP_dlamb(0)]

sel_temp = where(wlab_dbe_el_dEP_dlamb ne wlab_dbe_el_dEP_dlamb(0),dimsel_temp)
endwhile

wlab_dbe_el_dEP_dlamb_list = wlab_dbe_el_dEP_dlamb_list(1:*)
el_dbe_el_dEP_dlamb_list   = el_dbe_el_dEP_dlamb_list(1:*)
EP_dbe_el_dEP_dlamb_list   = EP_dbe_el_dEP_dlamb_list(1:*)
```

```
bl_dbe_el_dEP_dlamb_list   = bl_dbe_el_dEP_dlamb_list(1:*)
be_dbe_el_dEP_dlamb_list   = be_dbe_el_dEP_dlamb_list(1:*)

N7 = n_elements(wlab_dbe_el_dEP_dlamb_list)

;------------------------------------
;open and write output
;------------------------------------
print, " 3. Open and write output"

; Windows
OPENW, 1, path+ 'Out\' +'LinesInRatios.txt'
OPENW, 2, path+ 'Out\' +'ratios17-05-06.txt'
OPENW, 3, path+ 'Out\' +'ratios17-05-06_unbl.txt'
; Linux
;;OPENW, 1, path+ 'Out/' +'LinesInRatios.txt'
;;OPENW, 2, path+ 'Out/' +'ratios17-05-06.txt'
;;OPENW, 3, path+ 'Out/' +'ratios17-05-06_unbl.txt'
;OPENW, 1, 'Out/' +'LinesInRatios.txt'
;OPENW, 2, 'Out/' +'ratios17-05-06.txt'
;OPENW, 3, 'Out/' +'ratios17-05-06_unbl.txt'

PRINTF, 1, 'el    wlab      EP     bl   be'
for i=0, (N7-1) do begin
    PRINTF, 1, el_dbe_el_dEP_dlamb_list(i), $
      wlab_dbe_el_dEP_dlamb_list(i),$
      EP_dbe_el_dEP_dlamb_list(i), $
      bl_dbe_el_dEP_dlamb_list(i), $
      be_dbe_el_dEP_dlamb_list(i), $
      format='(F4.1,2x,F8.3,2x,F5.3,2x,F3.1,2x,F3.1)'
endfor

PRINTF, 2, ' r#  el1   wlab1    bl1 el2   wlab2    bl2 |dlamb|  |dEP|  |dbe|'
for i=0, (N5-1) do begin
    PRINTF, 2,i, el1_dbe_el_dEP_dlamb(i), wlab1_dbe_el_dEP_dlamb(i), $
           bl1_dbe_el_dEP_dlamb(i),                             $
           el2_dbe_el_dEP_dlamb(i), wlab2_dbe_el_dEP_dlamb(i), $
           bl2_dbe_el_dEP_dlamb(i),                             $
           abs(wlab2_dbe_el_dEP_dlamb(i)-wlab1_dbe_el_dEP_dlamb(i)),    $
      abs(EP2_dbe_el_dEP_dlamb(i)-EP1_dbe_el_dEP_dlamb(i)),             $
           abs(be2_dbe_el_dEP_dlamb(i)-be1_dbe_el_dEP_dlamb(i)),        $
           format='(I3,2x,F4.1,2x,F8.3,2x,I1,2x,F4.1,2x,F8.3,2x,I1,2x,F6.3,2x,F6.3,2x,F4.1)'
endfor

PRINTF, 3, 'el1   wlab1    bl1 el2   wlab2    bl2 |dlamb|  |dEP|   |dbe|'
for i=0, (N6-1) do begin
    PRINTF, 3, el1_u_dbe_el_dEP_dlamb(i), wlab1_u_dbe_el_dEP_dlamb(i), $
           bl1_u_dbe_el_dEP_dlamb(i),                              $
           el2_u_dbe_el_dEP_dlamb(i), wlab2_u_dbe_el_dEP_dlamb(i), $
           bl2_u_dbe_el_dEP_dlamb(i),                              $
           abs(wlab2_u_dbe_el_dEP_dlamb(i)-wlab1_u_dbe_el_dEP_dlamb(i)),              $
      abs(EP2_u_dbe_el_dEP_dlamb(i)-EP1_u_dbe_el_dEP_dlamb(i)),              $
           abs(be2_u_dbe_el_dEP_dlamb(i)-be1_u_dbe_el_dEP_dlamb(i)),              $
          format='(F4.1,2x,F8.3,2x,I1,2x,F4.1,2x,F8.3,2x,I1,2x,F6.3,2x,F6.3,2x,F4.1)'
endfor
CLOSE, 1
CLOSE, 2
```

```
    CLOSE, 3
    print, " "
    return
end;
```

E.2 Calibration.pro

```
;*********************************************************************;
;                                                                     ;
;   Compute the equivalent width ratios of the stars                  ;
;   and plot the calibration Teff vs ratios                           ;
;                                                                     ;
;*********************************************************************;

; required files :
;
; - ListStar.txt
; - ListFile.txt
; - Stars/all the files listed in ListFile.txt
; - Out/ratios17-05-06.txt
;
;*********************************************************************

; calling sequences :
;
;IDL> .r calibration.pro
;IDL> calib
;
;*********************************************************************

pro calib

    ;-----------------------------------
    ; Read input files
    ;-----------------------------------

    path = 'E:\Stage_IAC\IDL\IDL_aspid_07_06\'        ;path Windows

    ;reading the list of stars with their temperature
    readcol, path + 'ListStar.txt', $
             star, teff, dteff,  $
             FORMAT='A,F,F', SKIPLINE=2, /SILENT

    ;reading the list of daospec output files
    readcol, path + 'ListFile.txt', $
             nameDAO,       $
             FORMAT='(A)', SKIPLINE=2, /SILENT

    Nstar = n_elements(nameDAO)

    ;reading the list of ratios
    readcol, path + 'Out/'+'ratios17-05-06.txt', $
             rR, el1R, wlab1R, bl1R, el2R, wlab2R, bl2R, dlambR, EPR, dbeR, $
             FORMAT='I,F,F,I,F,F,I,F,F,F', SKIPLINE=1, /SILENT

    Nratio = n_elements(wlab1R)
```

```
;A is the array with all the read wavelength, EW and the error on EW for all the stars
;142 is the number of spectral lines we are interessted in.
;3 stays for the columns wlab, EW and dEW
A=fltarr(Nstar,142,3)

;rEW is the array where will be put all the EW ratios and the error on the
; ratio for each star
;2 stays for the columns rEW and drEW (error on rEW)
rEW = fltarr(Nstar,Nratio,2)

for i=0,Nstar-1 do begin

    ;reading the daospec output file for each star
    readcol, path + 'Stars/'+ nameDAO(i), $
      wobs, wrest, EW, dEW, qual, wlab, el, EP, lgf, bl, be, orig, $
      FORMAT='F,F,F,F,F,F,F,F,F,I,F,A5', SKIPLINE=2, /SILENT

    Nline = n_elements(wlab)

    ;filling the array A
    A[i,0:Nline-1,0]= wlab
    A[i,0:Nline-1,1]= EW
    A[i,0:Nline-1,2]= dEW

    ;------------------------------------
    ; Compute ratios
    ;------------------------------------

  for k=0, Nratio-1 do begin
      p1 = where (A[i,*,0] eq wlab1R[k])
   if (p1 ne [-1]) then begin
        p2 = where (A[i,*,0] eq wlab2R[k])
     if (p2 ne [-1]) then begin
      rEW[i,k,0] = A[i,p1,1]/A[i,p2,1]
      rEW[i,k,1] = rEW[i,k,*]*(A[i,p1,2]/A[i,p1,1]+A[i,p2,2]/A[i,p2,1])
     endif
   endif
  endfor

endfor

;----------------------------------------
; Plot calibration graphs in .eps files
;----------------------------------------

T_max=max(teff)
T_min=min(teff)
degree3=intarr(Nratio)+3
degree4=intarr(Nratio)+4
degree5=intarr(Nratio)+5
degree6=intarr(Nratio)+6
err=fltarr(Nratio)+1.

OPENW, 1, path + 'rEW.txt'
OPENW, 2, path + 'fit.txt'

for i=0, Nratio-1 do begin
```

```
r_max=max(rEW[*,i])
lambda1=wlab1R(i)
lambda2=wlab2R(i)
Nptsfit=100 ; number of x values to use for the fit

set_plot,’ps’
device, filename = path + ’Plot/’+’PlotRatio’+strtrim(i,1)+’.eps’,encapsulated=1,/color, $
        xsize = 12, ysize = 12

;define palette
tvlct,[0,255,0,0],[0,0,255,0],[0,0,0,255]


plot,rEW[*,i],teff,/nodata,xstyle=1,ystyle=1,$
yrange=[4400,6500],xrange=[-0.1,r_max+0.2],$
XTITLE=’ratio(’+strtrim(i,1)+") "+strtrim(lambda1,1)+’/’+strtrim(lambda2,1),YTITLE=’Teff(K)’
oplot, rEW[0:25,i,0], teff[0:25], psym= 4, symsize=0.75
oplot, rEW[26:37,i,0], teff[26:37], psym= 6, symsize=0.75
errplot, rEW[*,i,0], teff-dteff, teff+dteff
errplot_x, teff, rEW[*,i,0]-rEW[*,i,1], rEW[*,i,0]+rEW[*,i,1]

if (r_max ne 0.) then begin
   sel_rEW_temp = where(rEW[*,i] ne 0.0, dim_rEW_temp)
   if (sel_rEW_temp ne [-1]) then begin
     rEWtemp = rEW(sel_rEW_temp,i)
     if (n_elements(rEWtemp) ne 1) then begin
        tefftemp = teff(sel_rEW_temp)
        dteff_temp = dteff(sel_rEW_temp)
        x_fit=findgen(Nptsfit)*r_max/Nptsfit
        y_fitPoly3=fltarr(Nptsfit)
        y_fitPoly4=fltarr(Nptsfit)
        y_fitPoly5=fltarr(Nptsfit)
        y_fitPoly6=fltarr(Nptsfit)

       vect3=fltarr(degree3(i)+1,Nptsfit)
       for j=0,degree3(i) do vect3(j,*)=[x_fit^j]
       vect4=fltarr(degree4(i)+1,Nptsfit)
       for j=0,degree4(i) do vect4(j,*)=[x_fit^j]
       vect5=fltarr(degree5(i)+1,Nptsfit)
       for j=0,degree5(i) do vect5(j,*)=[x_fit^j]
       vect6=fltarr(degree6(i)+1,Nptsfit)
       for j=0,degree6(i) do vect6(j,*)=[x_fit^j]

       fitPoly3 = POLY_FIT(rEWtemp,tefftemp,degree3(i),/DOUBLE,$
                  MEASURE_ERRORS=dteff_temp,CHISQ=chisqPoly3, $
                  SIGMA=sigmaPoly3,YERROR=dyfit3,YFIT=yfit3)
       fitPoly4 = POLY_FIT(rEWtemp,tefftemp,degree4(i),/DOUBLE,$
                  MEASURE_ERRORS=dteff_temp,CHISQ=chisqPoly4, $
                  SIGMA=sigmaPoly4,YERROR=dyfit4,YFIT=yfit4)
       fitPoly5 = POLY_FIT(rEWtemp,tefftemp,degree5(i),/DOUBLE,$
                  MEASURE_ERRORS=dteff_temp,CHISQ=chisqPoly5, $
                  SIGMA=sigmaPoly5,YERROR=dyfit5,YFIT=yfit5)
       fitPoly6 = POLY_FIT(rEWtemp,tefftemp,degree6(i),/DOUBLE,$
                  MEASURE_ERRORS=dteff_temp,CHISQ=chisqPoly6, $
                  SIGMA=sigmaPoly6,YERROR=dyfit6,YFIT=yfit6)
```

```
              y_fitPoly3=fitPoly3#vect3
              y_fitPoly4=fitPoly4#vect4
              y_fitPoly5=fitPoly5#vect5
              y_fitPoly6=fitPoly6#vect6
              y_fitFunc =fitFunc#vect2[0:1,*]

              PRINTF, 1, 'ratio', i
              PRINTF, 1, 'Teff     dTeff    rEW       drEW'
              for j=0, Nstar-1 do begin
                PRINTF, 1, teff(j), dteff(j), rEW[j,i,0], rEW[j,i,1], $
                format='(F7.2,2x,F5.1,2x,F9.6,2x,F8.6)'
              endfor
              PRINTF, 1, ' '

              PRINTF, 2, 'ratio', i
              ;PRINTF, 2, 'y = a+bx+cx2+dx3 .. : a,b,c,d .. values =  '
              ;PRINTF, 2, fitPoly4
              ;PRINTF, 2, '1 sig uncertainty of IDL polynomial fitting'
              ;PRINTF, 2, sigmaPoly4
              ;PRINTF, 2, 'goodness of IDL 3rd degree polynomial fitting', chisqPoly3
              PRINTF, 2, 'goodness of IDL 4th degree polynomial fitting',chisqPoly4
              PRINTF, 2, 'goodness of IDL 5th degree polynomial fitting',chisqPoly5
              PRINTF, 2, 'goodness of IDL 5th degree polynomial fitting',chisqPoly6
              ;PRINTF, 2, 'error on yfit                     ', dyfit
              ;PRINTF, 2, 'xfit      yfit'
              ;for j=0, Nptsfit-1 do begin
              ;PRINTF, 2, x_fit(j), y_fit(j),$
              ;format='(F8.6,2x,F9.4)'
              ;endfor
              PRINTF, 2, ' '
          endif
        endif

       oplot, x_fit, y_fitPoly3, linestyle=2
       oplot, x_fit, y_fitPoly4, linestyle=3
       oplot, x_fit, y_fitPoly5, linestyle=1
       oplot, x_fit, y_fitPoly6, linestyle=5

       ;legend, ['2001','2004'],$
       ;          psym=[6,4],/fill,/bottom, box=0
       legend, ['Poly 3rd','Poly 4th','Poly 5th','Poly 6th'],$
               linestyle=[2,3,1,5],/fill,/bottom,/right, box=0

       endif

       device,/close
       ;set_plot,'x'

    endfor
    CLOSE, 1
    CLOSE, 2
    ;stop ; to avoid closing the pro so that can use print, help .. on the internal
     ;variables, from the terminal
    return
end;
```

F Notes taken on the data reduction using the ESO MIDAS UVES package

```
-----------------------------------------------------------------------------
Instructions on reduction of the UVES spectra, using MIDAS and Gasgano
-----------------------------------------------------------------------------

! For the UVES pipeline to work
-----------------------------------------------------------------------------


- enter in the working directory,
here /net/burdeos/scratch/alapini/Reduction/UVES06/FITS

>cd /net/burdeos/scratch/alapini/Reduction/UVES06/FITS

- type

>source /net/aspid/scratch/invsoft1/fluves/.tcsh_uves_env

- to enter MIDAS, type

> inmidas

- in MIDAS, type (only work in Aspid and in Celidonia, if want on other machine, ask
Nicolas to change the path)

Midas 002> @@ /net/aspid/scratch/invsoft1/fluves/ex/rb/pipe.prg


! Steps for the reduction
-----------------------------------------------------------------------------


1. Creat one directory with all the UVES fits (science & calib files)
copy thargood_2.tbl in this directory

2. load this directory in gasgano (File/add&remove files)

3. In gasgano, check groups of same config as science spectra
- same date
- same CCD/arm of the spectro (BLUE, RED)
- centered on the same wavelength (here BLUE346, RED580)
- for the RED, 2 groups RED580low and RED580up bc _l.bdf and _u.bdf files
created by split/uves
- same binning

- find the fmtchk, orderdef & wavefree files for each config (using the TPLID
column) , and note down their number (file column)

4. In MIDAS

---------------------------------------------------------------------------
4.1 to be done each time opening MIDAS
--------------------------------------

4.1
- creat display and standard graph windows
```

```
Midas 001> config/disp

- creat another display, used by reduce/uves

Midas 005> crea/disp 0 1000,600

4.2
- creat a catalogue with all the fits files of the working directory

Midas 025> crea/icat allfits.cat *.fits

- creat bdf files (_b.bdf for BLUE CCD, _u.bdf & _l.bdf for RED CCD)

Midas 025> split/uves allfits.cat

--------------------------------------------------------------------------
4.3 to 4.9 to be done once per group
--------------------------------------

4.3
Midas 003> predict/uves "name of the fmtchk file in bdf" thargood_2.tbl
"name of an output catalogue (e.g: primo.cat)"

- check in MIDAS_00 graph_3 if lower and upper left graph are centered in y=0. if
not do :

Midas> predict/uves "name of the fmtchk file in bdf" thargood_2.tbl
primo.cat ? "shift in y upper left graph","shift in y lower left graph"

e.g : ...? -1,2 shifts upper graph upwards of 1, lower graph downwards of 2
i.e: put the y value of the center, read on the upper and lower left
graphs (in this example, -1 and 2 are the y value read on those graphs)

4.4
Midas 004> orderp/uves "name of the orderef file in bdf" "name of the gle
catalogue (e.g: rlow.cat)" primo.cat

4.5
Midas 010> add/icat  rlow.cat l"central wlgth""CCD".tbl
(e.g l346BLUE.tbl,l580REDL.tbl, l580REDU.tbl)

Midas 011> add/icat  rlow.cat thargood_2.tbl

Midas 012> read/icat rlow.cat
Image Catalog:  rlow.cat
--------------
No    Name                Ident                              Naxis  Npix
#0001 o860L1x1.tbl        ORDER_TABLE_REDL
#0002 b860L1x1.tbl        BACKGR_TABLE_REDL
#0003 d860L1x1.tbl        DRS_SETUP_REDL
#0004 l860REDL.tbl        LINE_TABLE_REDL
#0005 thargood_2.tbl      LINE_REFER_TABLE

check - if all the files (5) are there,
      - if 860 (in the example) is the wavelength you are working on
      - if 1x1 everywhere (if a 2x2 appears : smth wrong)
```

```
4.6
Midas 014> waveca/uves "name of the wavefree file in bdf" rlow.cat
rlow.cat AUTO

4.7
- in MIDAS_00 graph_3 check resolution
if ~ 100 000 for slit 0.3 (check slit in the header of a science file in
gasgano), or ~80 000 for slit 0.5 -> OK
if not : pbr

- Put the wavelength sampling at a REASONABLE step, do :
check the min value of pixel size to put as sample value, do :

MIDAS>plot/cal
check min value for pixel size in MIDAS_00 graph_0

MIDAS>read/icat rlow.cat
check the name of the DRS_SETUP_REDL file

MIDAS>set/eche sample="the value checked"

MIDAS>savini/eche "name of the DRS_SETUP_REDL file" write

MIDAS>show/eche r
check if the new value of sample has been saved

4.8 Master Bias
MIDAS> crea/icat "name of the bias catalogue (e.g: rlowbias.cat)" "name of the 1st bias file"
(- check the name of the file in gasgano, same date, CCD, binning.
 - for blue spectra only, allfits.cat also gives us date, image size and type of file.
 Rq on allfits: - still need to check CCD (trick: size of the image gives
                  an idea of the CCD, blue and red CCD don't have the same size).
                - easy way to get the deuterium flats: LAMP,DFLAT
- ! no indication for red spectra. check type of file in
    gasgano)

MIDAS> add/icat rlowbias.cat "name od 2nd bias"
...
MIDAS>read/icat rlowbias.cat
Image Catalog:  biasrlow.cat
--------------
No    Name                Ident                         Naxis  Npix
#0001 UVES_2001_05_14T11:13:08_463_l.bdf BIAS              2 4096,2048
#0002 UVES_2001_05_14T11:13:55_838_l.bdf BIAS              2 4096,2048
#0003 UVES_2001_05_14T11:14:43_194_l.bdf BIAS              2 4096,2048

check size of the files are the same as science image(same config)
(!same binning)

MIDAS>master/uves rlowbias.cat rlow.cat
(creat the master bias and put its name in rlow.cat)

4.9 Master Flat

- similar to Master Bias
```

```
crea/icat
(check the name of the file in gasgano, same date, CCD, central wlgth, binning
 + check lamp (=ThAr) for BLUE CCD bc Deuterium lamp has spectral lines in the
upper blue part of the spectrum)

add/icat
read/icat

MIDAS>master/uves rlowflat.cat rlow.cat rlow.cat
(creat the master flat and put its name in rlow.cat)

Midas> read/icat rlow.cat
Image Catalog:  rlow.cat
--------------
No    Name                Ident                                  Naxis  Npix
#0001 o860L1x1.tbl        ORDER_TABLE_REDL
#0002 b860L1x1.tbl        BACKGR_TABLE_REDL
#0003 d860L1x1.tbl        DRS_SETUP_REDL
#0004 l860REDL.tbl        LINE_TABLE_REDL
#0005 thargood_2.tbl      LINE_REFER_TABLE
#0006 l860L1x1_1.tbl      LINE_TABLE_REDL1
#0007 l860L1x1_2.tbl      LINE_TABLE_REDL2
#0008 l860L1x1_3.tbl      LINE_TABLE_REDL3
#0009 mbREDL_1x1_l.bdf    MASTER_BIAS_REDL                         2 4096,2048
#0010 mf860_1x1_s04_l.bdf MASTER_FLAT_REDL                         2 4096,2048
#0011 bg_860_1x1_s04_l.bdf BKG_FLAT_REDL                           2 4096,2048

check - if all the files (11) are there
      - if 860 (wavelength you are working on) everywhere
      - if 1x1 everywhere (if a 2x2 appears : smth wrong)

--------------------------------------------------------------------------
4.10 to 4.14 to be done for each science spectra
------------------------------------------------

4.10 Change some values in the DRS_SETUP_REDL file

4.10.1 change slit value (parameter of Spectrum and Sky Extraction, do :

MIDAS> extract/image output = "name of science image.bdf"[@1500,<:@1500,>]
(1500 is the the # of the x column, < and > indicate all the lines in y)

MIDAS> assi/gra g,3
MIDAS> set/gra yaxis=100,400 xaxis=1000,1400 pmod=1

MIDAS> plot output
(In MIDAS_00 graph_3, see the orders of the science image, in the range chosen in set/gad
the slit is the width of an order)

MIDAS> get/gcursor
In MIDAS_00 graph_3, mesure the slit using the cursor. clic at each edge of an
order (avoid noisy bit). x values appear in MIDAS terminal. get delta(x).
exit window by right clic on the mouse

MIDAS>read/icat rlow.cat
check the name of the DRS_SETUP_REDL file
```

```
MIDAS>set/eche slit="value of delta(x)"
MIDAS>savini/eche "name of the DRS_SETUP_REDL file" write

MIDAS>show/eche e
check if the new value of slit has been saved
.............................................
Tip : copy the following bit and paste it directly in MIDAS terminal

assi/gra g,3
set/gra yaxis=100,400 xaxis=1000,1400 pmod=1
plot output
get/gcursor
.............................................
4.10.2 change ron and conad in ccdfilt (parameter of Cosmic Rays Filtering), do :

- in gasgano, in the header of the science image, check value of ron and conad

MIDAS>set/eche ccdfilt="ron value","conad value","sigma(eg 4.0)"
MIDAS>savini/eche "name of the DRS_SETUP_REDL file" write

MIDAS>show/eche c
check if the new value of ccdfilt has been saved
check if medfilt=1.0,1.0,100.0, if not do 4.10.3

4.10.3 change medfilt (parameter of Cosmic Rays Filtering), do :

MIDAS>set/eche medfilt=1.0,1.0,100.0
MIDAS>savini/eche "name of the DRS_SETUP_REDL file" write

MIDAS>show/eche c
check if the new value of medfilt has been saved

4.11 START EXTRACTION

MIDAS> show/eche b
check if BKGMTD=POLY (Method of background fitting). if not, do:

MIDAS> set/eche BKGMTD=POLY
MIDAS> savini/eche "name of the DRS_SETUP_REDL file" write

MIDAS> show/eche b
check if the new value of BKGMTD has been saved

Midas 029> @@ reduce_filt "science bdf file (the same used in 4.10)"
"output catalogue (e.g : last.cat)" rlow.cat P AVERAGE

- Backgound fitting plotted in MIDAS_00 display_0, graph_1, graph_2, graph_3

- check in MIDAS_00 graph_1, graph_2, graph_3 if fit (colored line) is good
- if yes (most of the time), right clic on MIDAS_00 display_0.
reduce_filt will continues running. do 4.11.2
- if no, right clic on MIDAS_00 display_0 and ctrl-c in MIDAS terminal.
reduce_filt will stops running. do 4.11.1

4.11.1 Background correction (following of method of bkgrd fitting)

- change order of the polynomial fitting (parameter of Background)
```

```
MIDAS> set/eche BKGPOL=1,2
(4 is the order in x, 5 in y)
MIDAS> savini/eche "name of the DRS_SETUP_REDL file" write

MIDAS> show/eche b
check if the new value of BKGPOL has been saved

Midas 029> @@ reduce_filt "science bdf file (the same used in 4.10)"
"output catalogue (e.g : last.cat)" rlow.cat P AVERAGE

- check in MIDAS_00 graph_1, graph_2, graph_3 if fit (colored line) is good
- if yes (always), right clic on MIDAS_00 display_0.
reduce_filt will continues running. do 4.11.3

(if no, right clic on MIDAS_00 display_0 and ctrl+c in MIDAS terminal.
reduce_filt will stops running. .... now, umm ... ask Alex ;) )

4.11.3 Cosmic ray filtering

- Cosmic rays plotted in MIDAS_00 display_0

if cosmic well spread on the image : ok, right clic on display_0 and let
reduce_filt finish its run

if cosmic along trends (lines) : bad. right clic on display_0 and ctrl-c on MIDAS
terminal. higher last number of medfilts, do:

MIDAS>set/eche medfilt=1.0,1.0,120.0
                               -----
MIDAS>savini/eche "name of the DRS_SETUP_REDL file" write

MIDAS>show/eche c
check if the new value of medfilt has been saved

4.11.4

Midas 029> @@ reduce_filt "science bdf file (the same used in 4.10)"
"output catalogue (e.g : last.cat)" rlow.cat P AVERAGE
when background on display_0 right clic to continue
when cosmic ray on display_0 right clic to continue

4.12
- creat a fits file from the reduced science image .bdf

Midas 159> outdisc/fits "name of output of reduce_filts (r_A_...bdf)" name=input?fits
creat a fits file, called "name".mt, in working directory (FITS/)

4.13
- in a terminal, in the FITS directory

>cp "name".mt ../Reduced/.
>mv ../Reduced/"name".mt ../Reduced/"name".fits

4.14
- check the reduced spectra "name".fits, using IRAF
```