

# THE UVES PARANAL OBSERVATORY PROJECT

## A LIBRARY OF HIGH-RESOLUTION SPECTRA OF STARS ACROSS THE HERTZSPRUNG-RUSSELL DIAGRAM

*WE PRESENT THE UVES PARANAL OBSERVATORY PROJECT, CONSISTING OF ACQUISITION, REDUCTION, AND PUBLIC RELEASE OF HIGH-RESOLUTION, LARGE WAVELENGTH COVERAGE, AND HIGH SIGNAL-TO-NOISE RATIO STELLAR SPECTRA OBTAINED WITH THE UVES INSTRUMENT OF THE ESO VERY LARGE TELESCOPE. DATA FOR ABOUT 400 STARS ACROSS THE HERTZSPRUNG-RUSSELL DIAGRAM HAVE BEEN TAKEN AND REDUCED BY MEMBERS OF THE PARANAL SCIENCE OPERATIONS TEAM AND MADE PUBLICLY AVAILABLE THROUGH A WEB INTERFACE AT [www.eso.org/uvespop](http://www.eso.org/uvespop).*

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**M**OST OF THE OBSERVATIONAL CONSTRAINTS to stellar astronomy come from low to medium resolution spectra obtained in spectral bands a few hundred nm wide or, in other cases, from high-resolution spectra in bands a few tens of nm wide. In spite of the capabilities of the existing instruments, there is a lack of a library composed of high-resolution spectra with complete optical coverage for stars representative of the entire Hertzsprung-Russell (HR) diagram. This is due to the fact that the best instruments are attached to largely over-subscribed telescopes, and are dedicated to very specific projects. At the same time, using large telescopes to observe bright targets is very inefficient, as overheads are comparable to, or even much longer than, open shutter times.

On Cerro Paranal, twilight time is normally used for calibration of the instruments in operation. At the beginning of each evening twilight, and at the end of several morning twilights, telescopes point to empty fields, in order to provide the calibrations of the various instruments with fresh sky flats. At the VLT Unit 2 Kueyen, the Nasmyth foci host two instruments dedicated to high-resolution UV and optical spectroscopy: UVES and FLAMES. The UVES calibration plan is restricted to spectro-photometric standard stars that are observed during the darker part of the twilights. With Kueyen and UVES, overheads are short enough that even the early evening twilight time (or late morning twilight) is sufficiently long to take a full spectrum of a bright star. Hence, the use of UVES during twilights appears well suited to build

up a library of stellar spectra with no impact on normal operations.

Members of the Paranal Science Operations Team have thus been authorized to make use of the brighter part of twilight times for a task of public interest, and have started the UVES Paranal Observatory Project (UVES POP): an on-going project of acquisition, reduction, and public release of high-resolution, large wavelength coverage, and high signal-to-noise ratio (SNR) stellar spectra. Telescope time was granted under DDT Prog. ID 266. D-5655(A).

The targets were selected in order to sample the various spectral types of the HR diagram, but the limited amount of time available during twilight (about 20 minutes) and the desire to obtain high SNR data, set the limiting magnitude of the targets, as a general rule, to  $V=7.5$ .

All the observed spectra cover almost completely the wavelength interval from 304 to 1040 nm (except for a few narrow gaps). With a slit width of 0.5", the achieved spectral resolution  $R = \lambda/\Delta\lambda$  is about 80000. For most of the spectra, the typical final SNR obtained in the  $V$  band is between 300 and 500.

The UVES POP library is the richest available database of observed stellar optical spectral lines. Many transitions and oscillator strengths are often only theoretically studied and a comparison with stellar spectra may permit one to refine or correct the theoretical predictions. The UVES POP library is thus an observational counterpart of atomic databases such as, e.g., the Vienna Atomic Line Database (see Kupka et al. 1999 and reference therein; see also [1]).

POP stellar spectra can be used for many different studies. For instance, one

can check thoroughly our capability of reproducing stellar spectra with model atmospheres and spectral synthesis codes, from very normal main sequence stars, to peculiar stars or less common objects; element abundances can be calculated with unprecedented accuracy for many different kinds of star; population studies may take special advantage of the large wavelength coverage of the POP star spectra (although it should be pointed out that UVES spectra are not absolute flux-calibrated due to slit losses); features of the nearby interstellar medium also appear in great detail in the intrinsically featureless spectra of the hottest observed stars. Note also that, although many of the observed targets appear to be well-known objects, it is probably not unreasonable to surmise that serendipitous discoveries may follow a close inspection of such a large and high-quality observational database – unknown and interesting signatures in bright stars might well have escaped detection so far. This is particularly true for the observed spectral region before the Balmer jump ( $\lambda=304-364.6$  nm), that represents an almost unexplored realm even for bright stars. Note also that in most of the cases *several* exposures of the same target are taken within a very short period of time, with identical settings. This might permit one to discover short-term spectral variability. Finally, it should be pointed out that the UVES POP library may help to improve stellar spectral classification: thanks to the large spectral coverage and the high resolution, one may discover spectral indicators that have escaped detection in previous studies.

The UVES POP library is also a user-friendly database for teaching purposes: several examples of stellar spectral fea-

tures may be promptly found and compared among each other, in particular thanks to a specially designed tool, the *Spectrum Preview Interface* (SPI) that is available at the UVES POP web site.

### TARGET SELECTION

Program stars fall into two groups, i.e., field stars, and stars belonging to two open clusters.

For field stars, the only selection criterion applied was to cover the largest possible variety of spectral types in the HR diagram, including peculiar objects, e.g., Ap and Bp stars, Wolf-Rayet stars, Be stars, and carbon stars. Most of the observed objects are brighter than 7.5 in the  $V$  band, and in the solar neighbourhood. Hence, most of the POP stars have solar metallicity. However, a few metal poor stars (with  $[Fe/H]$  ranging from  $-2.5$  to  $-0.5$ ) were also included in the target list. Spectral types were taken from SIMBAD and other more specialised catalogues, such as, e.g., the 14<sup>th</sup> General Catalogue of MK Spectral Classification (Buscombe 1999), and the General Cata-

**Table 1:** Wavelength intervals of the UVES POP observations in DIC1 and DIC2 mode

Mode	Setting name	Wavelength coverage	Optical path/arm
DIC1	346B	304 – 388 nm	blue
	580L	476 – 577 nm	red (lower chip)
	580U	584 – 684 nm	red (upper chip)
DIC2	437B	373 – 499 nm	blue
	860L	660 – 854 nm	red (lower chip)
	860U	866 – 1040 nm	red (upper chip)

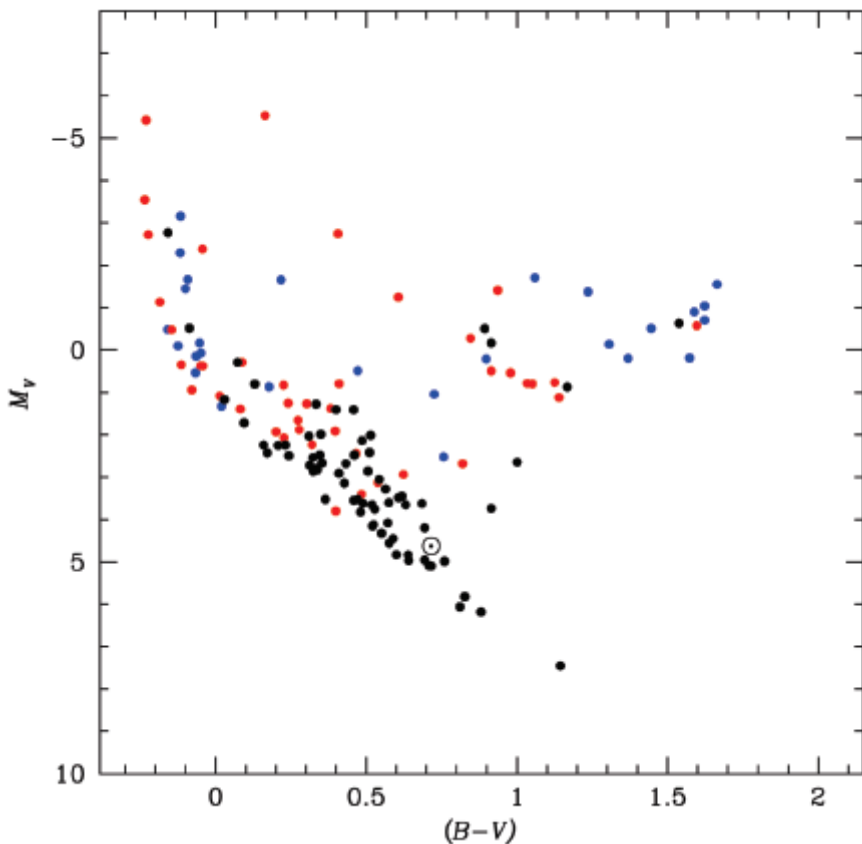
logue of Ap and Am stars (Renson et al. 1991). It should be noted that the spectral classification of the observed targets came from a quick search in the literature, and that in general the spectral type assigned to our targets *cannot be considered accurate or definitive*. Spectral reclassification might eventually be performed on the basis of UVES POP data. So far, more than 300 field stars have been observed. About 20 of them are extremely bright ( $V < 2.5$ ) and very

famous stars (Aldebaran, Betelgeuse, Rigel, etc.). These latter stars were specifically observed in order to allow easy comparison with the observations obtained with other spectrographs on smaller telescopes. The stars observed up to the moment of writing represent about 80% of the different spectral types and luminosity classes of the HR diagram. In Fig. 1 we show the colour-magnitude diagram of the observed field stars for which parallaxes and photometry could be found in the HIPPARCOS catalogue (ESA 1997).

Spectra have also been obtained for a number of (presumed) members of two selected open clusters, IC 2391 and NGC 6475 (M7). Due to the unforeseen move of FORS2 from Kueyen to Yepun in P66, the UVES service mode queues were sometimes undersubscribed. Hence, about 30 hours of telescope time were used for night-time observations of some faint objects in the two selected open clusters (IC 2391 in P66, from 7 to 12 February 2001, and NGC 6475 in P67, in the second half of August 2001). For target selection, extensive use has been made of *WEBDA*, a WEB database for open clusters [2]. In total about 50 stars of IC 2391 and about 30 stars of NGC 6475 have been observed. With the open cluster data, more specific scientific projects can be carried out, for example to accurately determine cluster membership, metallicity, and angular momentum distribution.

### INSTRUMENT SETUP

The Ultraviolet-Visual Echelle Spectrograph (UVES) instrument is described in detail by Dekker et al. (2000), in the instrument manual by Kaufer, D’Odorico, & Kaper (2003), and, more generally, in [3]. UVES is a very efficient high resolution spectrograph designed to operate from about 300 nm to 1100 nm. This wavelength range can be almost fully observed using two instrument modes (hence with two different sets of expo-



**Figure 1:** The colour-magnitude diagram of the field stars observed within the framework of the UVES POP.  $(B-V)$  and absolute magnitudes have been computed using parallaxes and photometry from the Hipparcos catalogue, and were not corrected for interstellar extinction. The colours blue, red and black indicate an accuracy on the parallax better than 20 %, 10 % and 5 %, respectively. Stars with parallax errors larger than 20 % are not plotted. The position of the Sun is also indicated.

ures), each of them characterised by the use of a special dichroic (DIC1 and DIC2). Dichroics are used to split the light beam coming from the telescope to feed the two arms of the spectrograph, the blue arm, and the red arm. The blue arm hosts an EEV 2K×4K CCD, and the red arm hosts a mosaic of two (EEV and MIT) 2K×4K CCDs. Table 1 gives the wavelength ranges covered by the UVES POP observations.

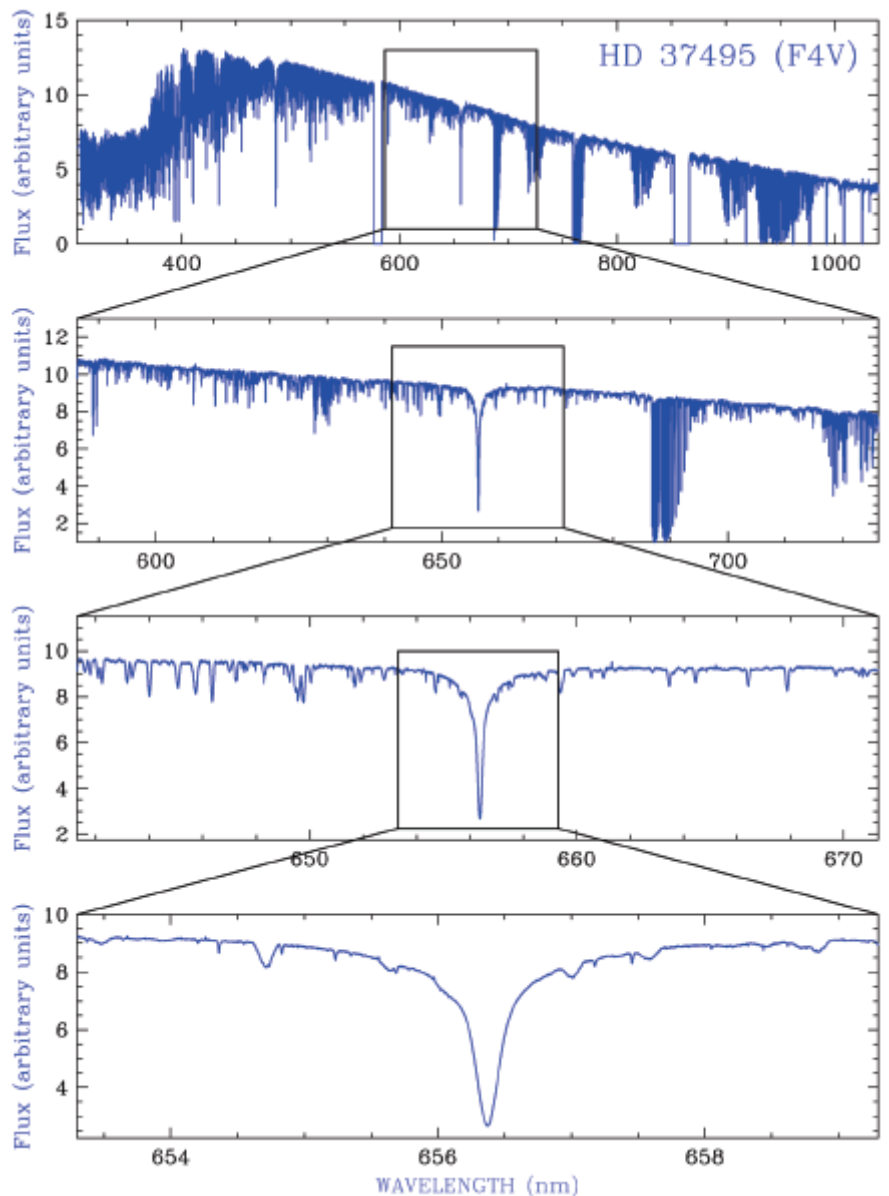
The use of a 0.5" slit width provides a spectral resolution of about 80000. Almost the full wavelength interval from 304 to 1040 nm is observed, but with a few gaps. Two main gaps, corresponding approximately to 577–584 nm and 854–866 nm, are due to the physical gap between the two chips of the red CCD mosaic. Because of this gap, the component at 854.2 nm of the famous CaII triplet around 860 nm is normally not covered in the UVES POP observations. However, for stars with blueshifted velocities  $\geq 70$  km/s (prior to the conversion of the wavelength scale to the heliocentric rest-frame) this component may become visible, and the one at 866.2 nm may enter into the gap. In addition, there are several small gaps, about 1 nm-wide each, due to the lack of overlap between the reddest echelle orders in the 860U setting.

The vast majority of stars were observed with the slits oriented along the parallactic angle, in order to minimize losses due to the atmospheric dispersion.

#### DATA REDUCTION

For this project, data reduction has been a particularly demanding task. The obvious problem is related to the *huge* amount of data that are involved, both in terms of science data and calibrations. A science exposure in dichroic mode (i.e., when both arms are used) takes about 46 Mbytes (12 Mbytes for the blue arm CCD, and 34 Mbytes for the two red arm CCDs). In fact, each star is observed with two instrument settings, and multiple exposures are taken for each setting. For each observing night, and for each instrument setting, five flat fields, five biases, one wavelength calibration, plus two special calibrations (one ‘order definition’ and one ‘format check’ frames) are taken. This corresponds to 1.25 Gbytes of calibration frames. The data delivered up to the end of P71 (namely science and calibration data for about 400 stars) occupy almost 100 DVDs!

UVES data obtained in service mode are routinely reduced by the ESO Garching *Data Flow Operations* (DFO) group using an automatic pipeline that is

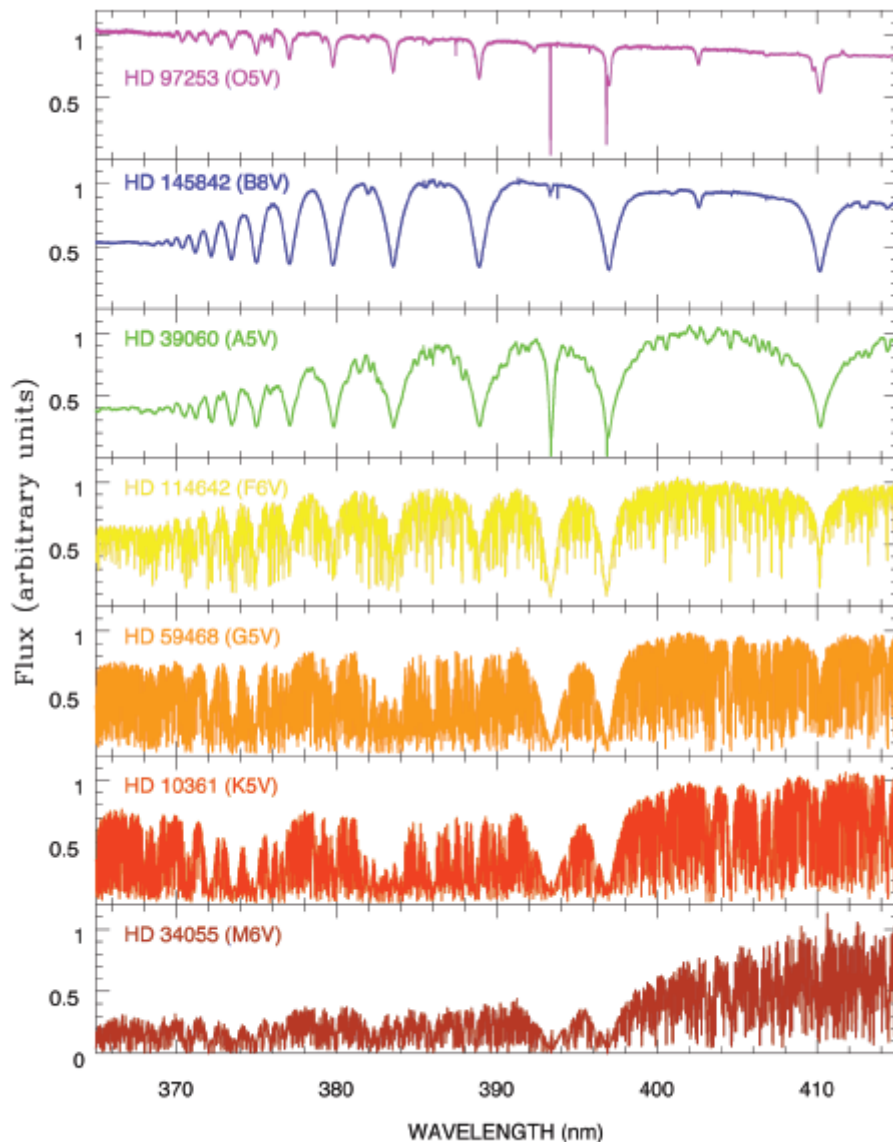


**Figure 2:** The overall spectral energy distribution of an F4V star (HD 37495) observed with UVES, together with several enlargements around the  $H\alpha$  absorption line. The quality of this spectrum is representative of the entire library: high SNR, high spectral resolution, large spectral coverage; on the other hand, some ripples around 800 nm (discussed in [5]) are visible. In the top panel, note also the gaps around 580 nm and 860 nm due to the physical gap in the CCD mosaic of the red arm.

described in Ballester et al. (2000) (see also [4]). Together with raw data, service mode UVES users receive pipeline products that are generally ready to be used for science. Unfortunately, POP data cannot be processed through the standard DFO pipeline in Garching, mainly because the software used by the DFO group is optimised for lower SNR spectra ( $\leq 100$ ). An *optimum* extraction algorithm is used, that assumes a Gaussian profile for the cross-dispersion flux distribution. However, the use of this method leads to poor results when applied to SNR  $\geq 100$  data (for details see [5]). For

this project, it has been found more appropriate to use an *average extraction* algorithm.

Therefore, it was decided to take care of the data reduction with the help of a dedicated Linux machine at ESO Vitacura facilities in Chile. A number of MIDAS routines and display tools have been designed for the specific format of UVES POP data, and for the specific requirements of the project, although the core of data reduction procedures is still the UVES context v1.2 of MIDAS. An automatic procedure has been developed to convert the wavelength scale of the spec-



**Figure 3:** The spectral region from 360 to 420 nm for a sample of stars of the OBAFGKM spectral types. All Balmer lines from H $\delta$  down to the Balmer jump are clearly visible in the hotter stars. In the O star spectrum (top panel), the two sharp absorption features at about  $\lambda$ 393.4 nm and 396.8 nm are due to interstellar CaII.

tra to heliocentric rest-frame, average multiple individual exposures (with cosmic ray rejection), and merge the spectra from different settings all together. During this process, all individual reduced spectra were extinction-corrected and flux-calibrated as explained in [6] (see also Hanuschik 2003) using the master response curves determined by ESO Garching Quality Control [7]. Note that because of slit losses occurring when a 0.5" slit width is used under variable seeing conditions, the final flux spectrum is not suitable for absolute flux measurement, hence one can recover only the

shape of the star's spectral energy distribution.

The final result is one individual spectrum per star (plus its associated variance) covering the whole optical range from about 304 to 1040 nm. Some examples of reduced and globally merged files are shown in Figs. 2 and 3. Figure 2 shows the large spectral coverage of UVES POP observations, that are at the same time characterised by a high SNR and a high spectral resolution. Figure 3 is an example of the variety of stellar spectra observed across the main sequence of the HR diagram.

## QUALITY CONTROL (QC)

A number of checks were performed on the reduced spectra, and results are reported in a dedicated *logfile* that is released together with the data. First, target coordinates written in the fits-headers are cross-checked using the SIMBAD database, or with specific literature, to make sure that the target is correctly identified. The epoch of the various observations is also noted down, in particular it is checked that all observations of a given star have been taken during the same night. If not, a warning is issued in the logfile, bearing in mind the possibility that some stars in the sample are actually variable.

Finally, a close inspection of the reduced spectra is performed independently by two members of the team. In some cases, science frames do not pass the quality check and are rejected (for instance, spectra with too low SNR, or saturated, or for which extraction has failed, or those that for any reason have a quality substantially lower than expected). Note that even if the worst cases are rejected, the released spectra may still be affected by some problems like ripple effects (due to inaccurate blaze function correction) and lower-quality extracted order merging. These well-known problems are documented in [5].

## DATA RELEASE AND SPECTRUM PREVIEW INTERFACE (SPI)

The data are released through an ESO WEB page: <http://www.eso.org/uvespop>. The home page gives some general information about the project, and points to three main tables: *i*) stars belonging to the open cluster IC 2391, *ii*) stars belonging to the open cluster NGC 6475 (M7), and *iii*) field stars ordered by spectral types. A fourth table is devoted to some of the brightest ( $V < 2.5$ ) stars in the Southern Hemisphere.

All tables are organized in a similar way. Each table entry corresponds to an individual star, and includes links to the SIMBAD database, to the UVES reduced spectra, and to a QC logfile.

For each star, the reduced spectra are made available – through a direct link – in the form of seven gzipped tar files, plus one fits table. Each tar file includes a number of fits files that are the straight output of the MIDAS UVES pipeline modified for this project. Six tar files are relevant, respectively, to the six observed spectral ranges, i.e., 346B, 437B, 580L, 580U, 860L, and 860U. Each of these tar files includes all individual reduced spectra and the associated variance spectra.

Since the merging of the various echelle orders is a delicate step of the data reduction process, data release comes along with a seventh tar file, containing the pipeline products *prior to merging the orders*, plus the sky spectra. Unmerged spectra may be used to check if some features are due to an artifact produced by the merging, and in some cases, may be preferred to merged spectra for science use.

The naming convention is self-explanatory. All file names explicitly refer to the star's name (generally the entry in the Henry Draper Catalogue), the instrument setting, and the time-stamp, whenever applicable. For instance, a file called `hd123456_437B_2001_03_21:01:15:00.fits` corresponds to the spectrum of star HD 123456 obtained using the 437B setting and observed on the 21<sup>st</sup> of March 2001, at 01:15:00 UT (date-stamp in fact corresponds to the time of shutter opening).

Ideally, the very final product is the fits table that is obtained by averaging/merging all final pipeline products as explained before. This table includes the star's spectrum and its variance. It is available through a direct link from the WEB tables, and its name only refers to the target name (e.g., `hd123456.tfits`). This file should be used with some caution. For instance, it may come from spectra taken at distant epochs, and, in the case of variable stars, different spectral regions may have been produced under different physical conditions. Moreover, the globally merged file may come from original spectra of uneven quality in terms of, for instance, blaze function correction. Users should check the QC logfile and the fits headers of individual spectra. Note also that, since the globally merged spectra have their wavelength scale converted to the heliocentric rest-frame, telluric lines, that in the observed frame are fixed in wavelength, appear *mis-aligned*. Telluric lines appear at the correct wavelengths only in the spectra included in the gzipped tar files. However, in many cases, and for many applications, the fits table is close to the best product that can be

obtained out of the original raw data.

It should be finally stated that the UVES POP reduced data are the result of a *mass production* process, that cannot be tuned to individual cases. Hence, some problems will remain in the final products. For individual stars, better results may possibly be obtained by retrieving the raw data and corresponding calibrations at the ESO UVES archive [8] using program ID 266. D-5655(A).

A collection of basic cgi plotting routines using PGPHERL and CFITSIO perl allows the user to overview the merged spectrum of a given star in the desired spectral range. These routines form the *Spectrum Preview Interface* (SPI), a display tool that has been specifically created for the public release of UVES POP spectra. Users can choose to have the spectrum displayed in GIF format, or to save it as a postscript file. A third possibility allows the user to download the spectrum as an ASCII file in a given wavelength interval.

The SPI can be activated in two different ways: *i*) through a special link from the table with the target list, and *ii*) through the main SPI web page. The former is the most basic and probably the most convenient method to select and display *individual* spectra. The latter method permits one to perform elementary searches through the POP database (e.g., for a given name string and/or spectral type and/or spectral peculiarity) and to display up to five spectra altogether. Overplotting has two options: spectra can be stacked together, or shifted along the *y* direction.

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#### WEB LINKS CITED IN THIS PAPER

- [1] The VALD database:  
<http://www.astro.univie.ac.at/~vald/>
- [2] The WEBDA database:  
<http://obswww.unige.ch/webda/>
- [3] The UVES web pages:  
<http://www.eso.org/instruments/uves/>
- [4] The UVES pipeline:  
<http://www.eso.org/observing/dfo/quality/UVES/pipeline/>
- [5] Problems with the pipeline reduced spectra:  
[http://www.eso.org/observing/dfo/quality/UVES/pipeline/pipe\\_reduc.html#problems](http://www.eso.org/observing/dfo/quality/UVES/pipeline/pipe_reduc.html#problems)
- [6] How to flux calibrate UVES data:  
<http://www.eso.org/observing/dfo/quality/UVES/qc/response.html>
- [7] The UVES master response Curves:  
[http://www.eso.org/observing/dfo/quality/UVES/qc/std\\_qc1.html#response](http://www.eso.org/observing/dfo/quality/UVES/qc/std_qc1.html#response)
- [8] The ESO UVES archive:  
<http://archive.eso.org/wdb/wdb/eso/uves/form>