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Building up a database of spectro-photometric standard stars from the UV to the near-IR: a status report✦

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ABSTRACT

We present a project aimed at establishing a set of 12 spectro-photometric standards over a wide wavelength range from 320 to 2500 nm. Currently no such set of standard stars covering the near-IR is available. Our strategy is to extend the useful range of existing well-established optical flux standards into the near-IR by means of integral field spectroscopy with SINFONI at the VLT combined with state-of-the-art white dwarf stellar atmospheric models. As a solid reference, we use two primary HST standard white dwarfs. This ESO "Observatory Programme" has been collecting data since February 2007. The analysis of the data obtained in the first year of the project shows that a careful selection of the atmospheric windows used to measure fluxes and the stability of SINFONI make it possible to achieve an accuracy of 3-6% depending on the wavelength band and stellar magnitude, well within our original goal of 10% accuracy. While this project was originally tailored to the needs of the wide wavelength range (320-2500 nm) of X-shooter on the VLT, it will also benefit any other near-IR spectrographs, providing a huge improvement over existing flux calibration methods.

Keywords: spectro-photometric standard star, near infrared, X-shooter, calibration

1. PROGRAMME

1.1 Motivation

The aim of this programme is to establish a set of spectro-photometric standards over a broad wavelength range from 320 to 2500 nm. While there is a well established and widely used set of high quality optical spectro-photometric standard stars (in particular Oke[1]; Hamuy et al.[2,3]), we still lack a complementary set of comparable quality for the near-infrared (near-IR). Observations of white dwarfs with HST spectrographs and atmospheric modeling have established 3 stars as primary standards (~1% accuracy) for the wavelength range 115-2500 nm (Bohlin[4]). A set of near-IR spectro-photometric standards adequate for routine operations of ground based near-IR spectrographs simply does not exist at the moment. The currently used methods for estimating the absolute flux calibration of near-IR spectra are: (i) use the near-IR broad band magnitude of the telluric standard that has been observed for a given science exposure (e.g. from 2MASS); (ii) alternatively, when it is known, use the broad band magnitude of the scientific target itself to scale the near-IR spectrum. These methods are usually no more accurate than 20-30%.

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✦Based on observations made with ESO Telescopes at the La Silla Paranal Observatory under programme ID 278.D-5008

1.2 Strategy and instrumental setup

Our strategy is to extend the useful range of the well established optical flux standards from Oke[1] and Hamuy et al.[2,3] into the near-IR using SINFONI IFU in no-AO mode (field-of-view 8”×8”). This choice of instrument provides sufficient spectral resolution to peer through the forest of telluric absorption lines and OH emission lines while avoiding uncertainties related to slit losses. Using three primary HST white dwarf standard stars as a reference, our goal was to achieve about 10% accuracy. Flux measurements are done in a few carefully selected windows where atmospheric transmission is >99%. Interpolation between these measurements is done applying state-of-the-art stellar atmosphere models for the white dwarfs.

1.3 HST white dwarf standard stars

HST instruments provide the best available spectro-photometry since the observations do not suffer from atmospheric contamination. By using a combination of e.g. STIS and NICMOS a wavelength range from the far ultraviolet to the near infrared can be observed. The HST standard star network is based on three primary standard stars (Bohlin[4]) which we have adopted also for our purposes – only two (GD 71 & GD 153) of which can be observed from the Southern hemisphere. These stars are pure hydrogen white (DA) dwarfs (WDs). Hence, they combine excellent flux measurements – observed above the atmosphere – and the simplest chemical composition of the atmosphere treated by a state-of-the-art NLTE model (Hubeny[5]). The WD fluxes show an internal consistency of <1% when compared to their model spectral energy distributions (SEDs). They are the best available reference for a network of standards stars in the near-IR.

1.4 Atmospheric modeling of the secondary standards stars

The secondary standards stars have been selected from existing lists for the UV and visible domain. While the emphasis is on WDs, other stars have also been included to provide the required coverage in RA and Dec. Also, these WDs usually do not have pure hydrogen atmospheres requiring a proper treatment of their chemical composition. The selected secondary standards have been observed with UVES in the past and we use the archival data as input to plane-parallel, static, and chemically homogeneous models computed with the Tübingen NLTE Model Atmosphere Package (TMAP, Werner et al.[6], Rauch & Deetjen[7]). All elements from hydrogen to nickel can be considered (Rauch[8]). These models are then used to interpolate in between observed fluxes to derive an absolute flux table for each Secondary Standard across the full wavelength range.

1.5 Status Observing Programme

This Observatory programme (278.D-5008) is not in competition with science programmes from the user community since it is executed as filler observations during periods of poor seeing but under photometric conditions. First observations took place in February 2007 and ever since a steady stream of observations making use of SINFONI in less than perfect seeing but photometric conditions has been performed. The overall progress of the observing programme as of May 30th 2008 is shown in Figure 1. For each star, the dark column shows the levels of completion of validated photometric data, with 100% denoting the goal of 10 observations for each secondary standard star. So far more than 40% of the observing programme has been completed.

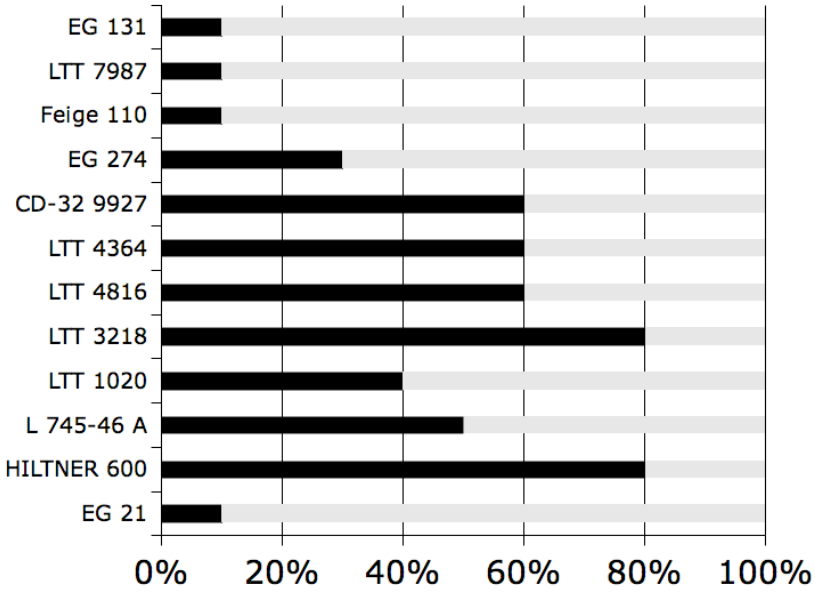

Figure 1: Status of the observing programme. The goal is to obtain a minimum of eight (goal ten) observations for each star.

2. DATA REDUCTION AND ANALYSIS

2.1 Observations and pipeline data reduction

Each star is observed in the J (resolving power R=2000) and the H+K (R=1500) setting following an Object-Sky-Sky-Object pattern with a dither of 0.5" so that the star does not fall twice on the same pixels. For each observing night we require to observe at least one of our primary standards. Exposure times range from 10s/band to 300s/band for the faintest stars (HST primaries).

All data are reduced using the SINFONI pipeline. It produces sky subtracted, wavelength calibrated data cubes. The whole reduction chain works well in general but in the case of our careful analysis we have identified two problems that seriously affected the computation of the absolute efficiency:

- During wavelength linearization, the flux was not fully conserved which caused a systematic error of the order of 5%. This problem was traced to a software bug and has been resolved.
- Normalization of the flat-field had been inadequate resulting in a wrong efficiency computation. We are skipping the flat-fielding step for the time being. A better normalization method involving filtering has been developed and will be implemented in the next release of the pipeline.

2.2 Extraction of the photometry

We have defined a set of 8 photometric windows where the atmospheric transmission is greater than 99% and free of strong OH sky lines. Table 1 gives the wavelength range for each window. Figure 2 shows the atmospheric absorption

spectrum and the sky emission spectrum, at the resolution of SINFONI in the J band windows. For each observation of a star, eight images are obtained by collapsing the wavelength calibrated data cube in the corresponding wavelength range to our eight atmospheric windows. For each image, the total flux is computed by fitting a Moffat point spread function (PSF) to the data (see Figure 3). Although most observations were taken under poor seeing conditions according to the DIMM seeing monitor, we observe in a substantial number of cases an image quality better than 0.5" in the K-band and at the red end of the H-band. In these conditions, PSF fitting fails because the PSF is under-sampled in one direction (SINFONI spaxel size in the 8"×8" field-of-view mode is 0.125"×0.25"). An encircled energy vs. radius diagram is then built out to a radius of 2.5". Residual sky background correction is computed to ensure a flat curve and the total number of counts is extracted (see Figure 4).

Table 1: Atmospheric transmission windows used to compute photometric points

Atmospheric Window	λ_{Start} [μm]	λ_{End} [μm]
J1.240	1.2329	1.2474
H1.547	1.5450	1.5490
H1.592	1.5885	1.5950
H1.627	1.6250	1.6300
H1.681	1.6720	1.6890
K2.141	2.1345	2.1480
K2.167	2.1550	2.1780
K2.192	2.1890	2.1940

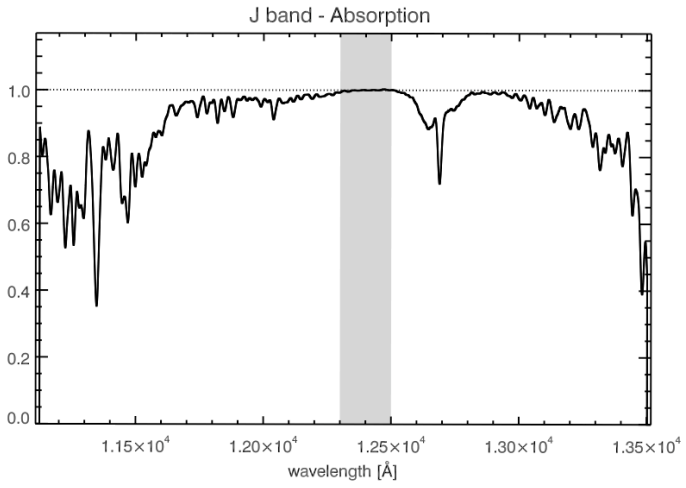

Figure 2: The J1.240 atmospheric window. Telluric absorption spectrum at R= 2000 as a continuous black line. The gray area shows the selected atmospheric window.

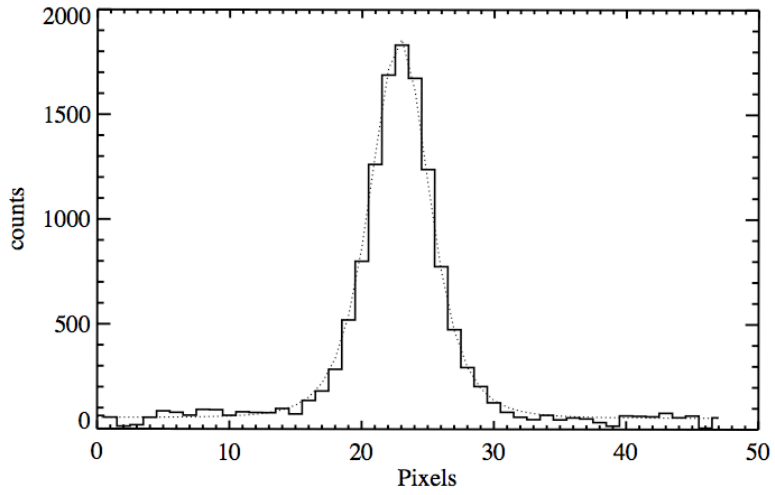

Figure 3: Example of a Moffat PSF fitting. The histogram shows the data and the dotted line represents the best fit.

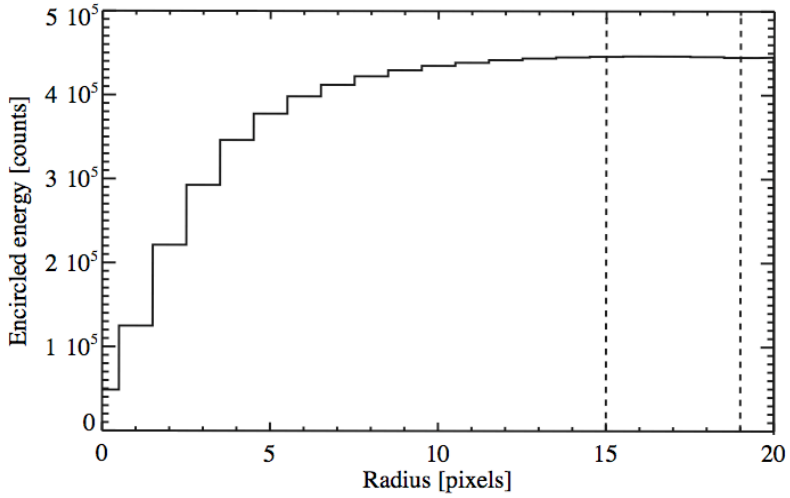

Figure 4: Example of an encircled energy vs. radius diagram used to extract the photometry in case of good (<0.5") seeing conditions. Vertical dotted lines show the region where residual sky background was computed.

3. PRELIMINARY RESULTS

3.1 Overall system efficiency

Using all 26 photometric measurements of our Primary Standards, we have derived the overall system throughput of SINFONI+Telescope in our 8 transparent atmospheric windows. Our results, shown in Figure 5, are in reasonably good agreement with SINFONI commissioning data obtained after science detector upgrade measurements in the J- and H-bands. Our measured efficiency in the K-band is significantly better (30% vs. 25%) than previously reported. During one of the observing runs, two of our Primary Standards (GD 71 and GD 153) were observed consecutively and provide results consistent within 5% in all windows.

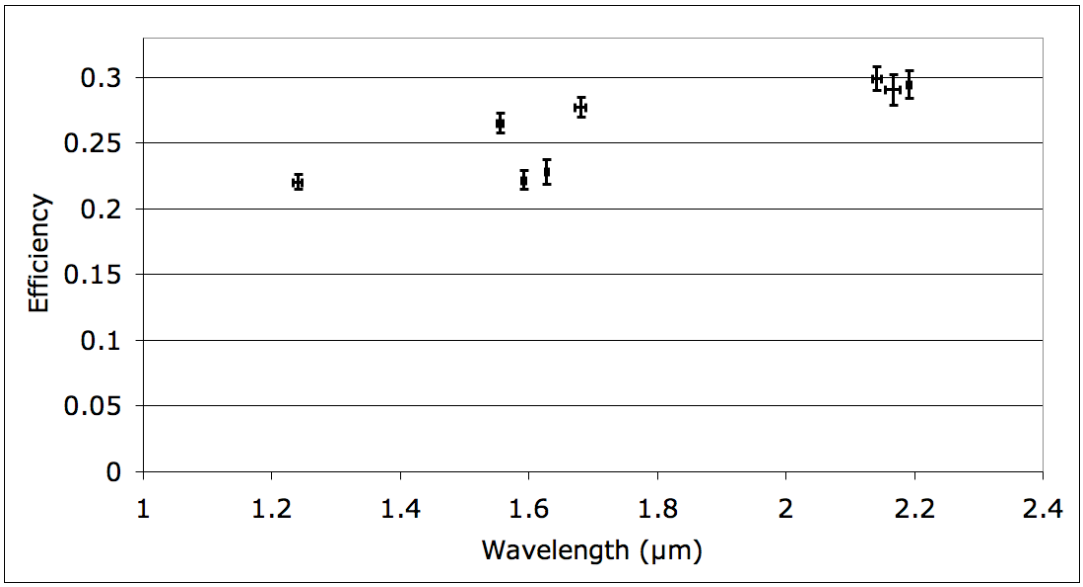

Figure 5: Overall SINFONI system efficiency in the J and H+K settings measured in the eight near-IR atmospheric absorption windows we have selected. Vertical error bars show the dispersion of measurements obtained over 26 nights. Horizontal error bars represent the width of each window.

3.2 Photometry

So far, sufficient data (8 observations) have been collected for two stars to enable us to estimate the overall photometric accuracy achievable. For Hiltner 600, the brightest star in our sample (K_{AB}~12), the standard deviation over our eight independent measurements is below 2.5% in all 8 windows. On the other hand, for LTT 3218 which is ~1.5mag fainter than Hiltner 600, we measure a dispersion below 4% in all windows. For the faintest of our secondary standards (LTT 4816, K_{AB}~15.8) the dispersion over 6 observations we have obtained so far is below 6%. These results – although still preliminary – clearly demonstrate the feasibility of our programme to deliver accurate flux calibrated spectra in the near-IR. Our initial goal of 10% accuracy should certainly be reached (see Fig. 5). In Figure 6, we show four examples of absolutely calibrated spectra from the UV to the near-IR and Figure 7 shows all individual measurements for Hiltner 600 in three of our atmospheric windows.

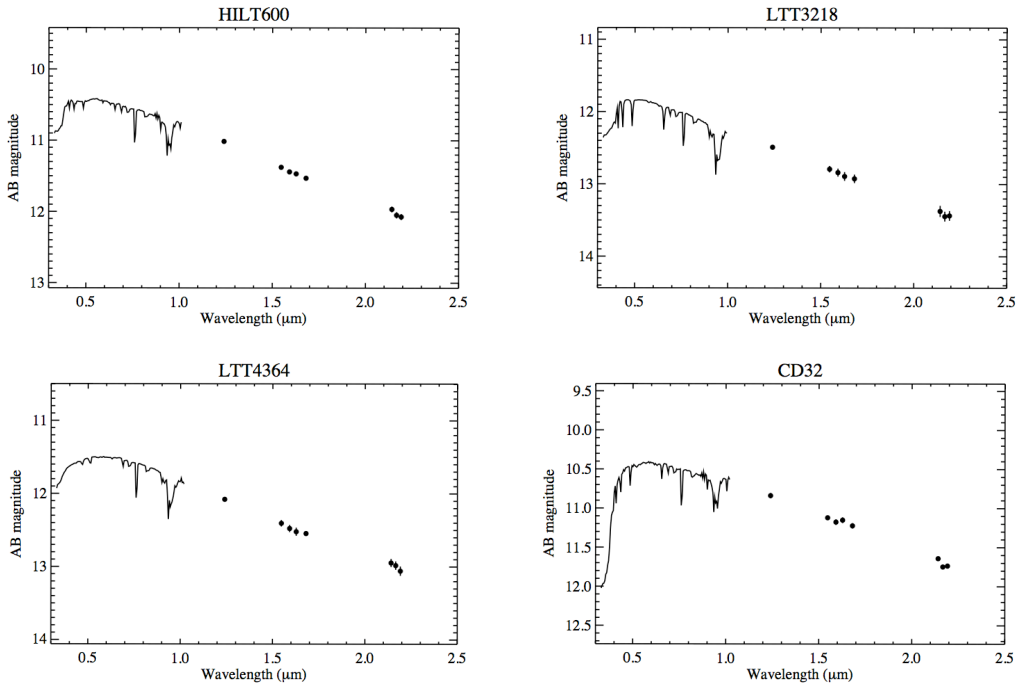

Figure 6: Spectra of four Secondary Standard stars for which we have more than five observations (Hiltner 600, LTT 3218, LTT 4364, CD-32 9927), from the UV to the near-IR. Our photometric points are shown as filled dots while the UV/Optical line shows data from Hamuy et al.[2,3].

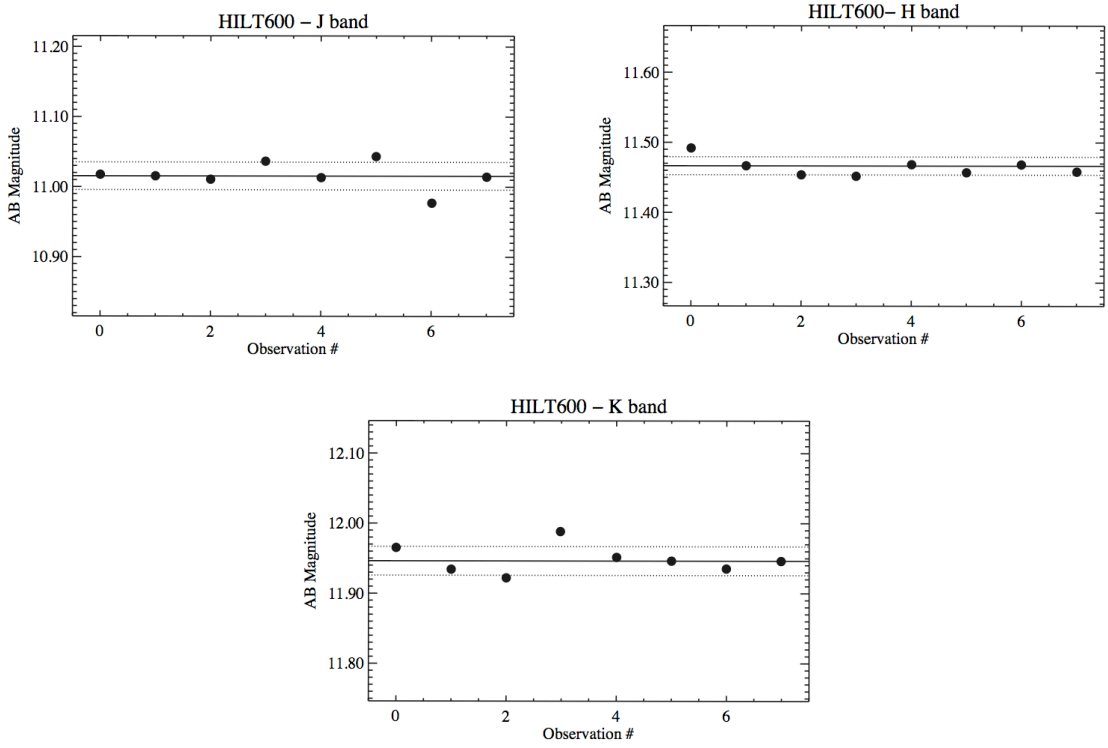

Figure 7: The eight flux measurements we have obtained in J1.240, H1.627 and K2.141 windows for Hiltner 600. The solid line indicates the median flux and the dotted lines mark the standard deviation.

3.3 Interpolation between transparent atmospheric windows

The accuracy we reach with the SINFONI data can be transferred to any wavelength by interpolating between our 8 absorption free windows using modeling as described in Section 1.4. To this end we used reprocessed UVES archival data[9]. Figure 8 shows the first results we obtained on EG 274 using TMAP simulations with parameters (T_{eff}=24276 K, log g=8.01, pure hydrogen model) from Holberg et al. [10]. Observations and modeled spectrum are fully consistent within the measured errors.

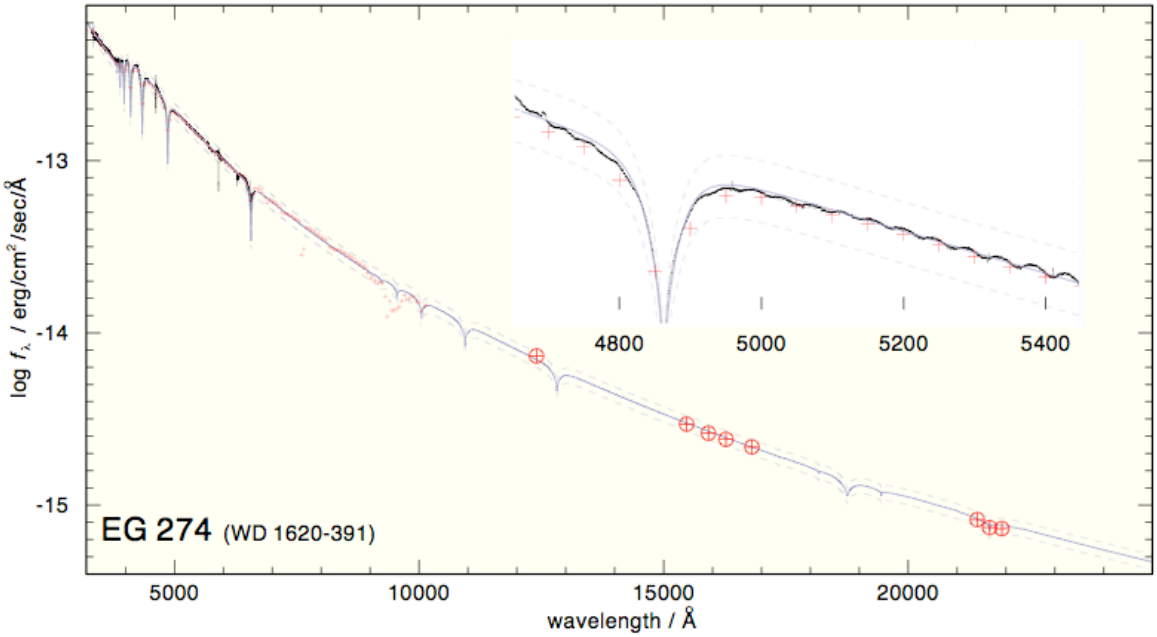

Figure 8: Comparison of a synthetic spectrum (gray line, dashed gray lines indicate ±10% of the flux level) of EG 274 (calculated with TMAP, T_{eff}=24276K, log g=8.01, pure hydrogen model) with VLT/UVES observations (smoothed, for clarity, with a Gaussian of 0.2Å). Hamuy's magnitude tables are indicated by "+" signs (red in electronic version). SINFONI measurements are denoted by cartwheel signs (red, the respective errors are smaller than the signs!). Please note that the SINFONI measurement centered at λ=21665Å covers HI λ21661.2Å Brγ). The insert shows a magnification of the wavelength region 4650Å < λ < 5450Å.

4. CONCLUSIONS

We have reported on the status of an Observatory Programme at ESO establishing spectro-photometric standards over the wavelength range 320-2500 nm. More than 40% of the observations have been obtained and the programme is ongoing. While the analysis is still preliminary, a careful selection of the atmospheric windows and the stability of SINFONI make it possible to achieve an accuracy of between 2% and 6%. A good understanding of error sources has been developed. The limiting factor for quantitative flux calibration with a slit-based spectrograph such as X-shooter will probably be slit losses. For the future we will determine the atmospheric extinction correction based on dedicated observations. Also we are working to obtain good atmospheric models for all secondary standards stars based on archival UVES data. The set of standards stars will be put to first use during commissioning of X-shooter in late 2008 and will be made available for supporting routine observations of near-IR spectrographs. Looking further into the future, ELTs are expected to work at IR wavelengths for a large fraction of their time; hence the establishment of a grid of suitable IR standard stars is very important.

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