

Flux Calibration of Medium Resolution Spectra from 300 nm to 2500 nm — Model Reference Spectra and Telluric Correction

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A procedure to obtain reference spectra for flux standard stars from stellar model atmospheres is described. This procedure allows users to derive instrumental response curves from 300 nm to 2500 nm. The technique was developed using X-shooter spectra, but is general and can also be applied to higher resolution spectra. In addition an automatic method has been defined to correct for moderate telluric absorption using telluric model spectra with very high spectral resolution that can easily be adapted to observed data.

Introduction

Accurate flux calibration of astronomical spectra requires flux calibrators with known absolute fluxes that are accessible with the same spectrograph used for the science targets. With the arrival of new generations of spectrographs that cover wide wavelength ranges and produce relatively high resolution spectra (e.g., X-shooter on the Very Large Telescope [VLT]), known and well-tested spectro-photometric standard star catalogues

(e.g., Hamuy et al., 1992; 1994) are no longer adequate for spectral flux calibration. These catalogues do not extend to the near-infrared (NIR) and/or are too coarsely sampled to permit the flux calibration of medium to high resolution spectra.

In this article, we describe a procedure to obtain calibrated model spectra for flux standard stars covering the wavelength range from 300 nm to 2500 nm. These spectra are useful for deriving consistent instrumental response curves over this wide range of wavelengths with a spectral resolving power of up to 40 000, and possibly more. They may also be useful for spectrographs delivering lower resolution data (e.g., FORS2), in order to calibrate small-scale variations of the detector response.

In order to compute response curves for an instrument from observed and model spectra, the effect of the Earth's atmosphere must be removed from the observed spectra. A method for fast and efficient removal of telluric absorption features is described. This method is sufficiently accurate for the intended purpose of deriving response curves and can be adapted for any other instrument, provided that the spectra are of sufficient resolution between 600 nm and 2500 nm and the positions of the stellar lines are known.

More details of the flux calibration procedure and the correction for telluric absorption can be found in Moehler et al. (2014).

Sample selection

Spectral flux calibration utilises as reference either well-calibrated observations or a spectral model of a standard star. The advantage of using a model is that it is noiseless, and does not include features imposed by the terrestrial atmosphere. Flux calibration requires the ratio of an observed spectrum and the reference spectrum and such a ratio is less sensitive to errors in the wavelength scale if the spectrum is smooth and featureless. Therefore, the ideal star to be used as a spectral flux standard has a smooth and featureless spectrum that can be accurately modelled with a minimum

number of parameters. The (photometrically uncalibrated) model spectrum of a star can be used to derive the shape of the response curve of an instrument and can therefore be used to test and improve the model spectra of other stars. If an absolute flux calibration is intended, the spectral models must be accompanied by accurate absolutely calibrated (spectro-)photometric observations at some wavelengths within the wavelength range covered by the model spectrum.

For the current work, we therefore searched for stars fulfilling the following criteria:

- hot white dwarfs and hot subdwarfs in order to be able to model their spectra;
- located in the southern hemisphere;
- available flux information;
- available X-shooter spectra taken with a wide (5-arcsecond) slit to minimise slit losses.

This selection resulted in six standard stars, namely EG 274, GD 71, GD 153, LTT 3218, LTT 7987 (all hot DA white dwarfs), and Feige110 (a hot subdwarf), which also have photometric information in the near-infrared wavelength range (Vernet et al., 2008; Bohlin et al., 2001). To verify the possible influence of mismatched stellar features we also selected a star that has a spectrum free of absorption lines between 300 nm and 2500 nm, namely L97-3 (a DC white dwarf).

Identifying the best model spectra

The spectra of our standard stars include strong hydrogen lines (and in the case of Feige 110 also helium lines) that need to be properly modelled in order to sample the response of an instrument on scales of some nanometres.

For the past 20 years the physical parameters of hot white dwarfs and other hot, high-gravity stars have been determined by fitting the profiles of the hydrogen (and/or helium) absorption lines in their optical spectra (Bergeron et al., 1992; see Figure 1, left panel, for an example). This method has the advantage that it is sensitive to changes in temperature and surface gravity at high effective temperatures, when optical and near-infrared photometry become insensitive to

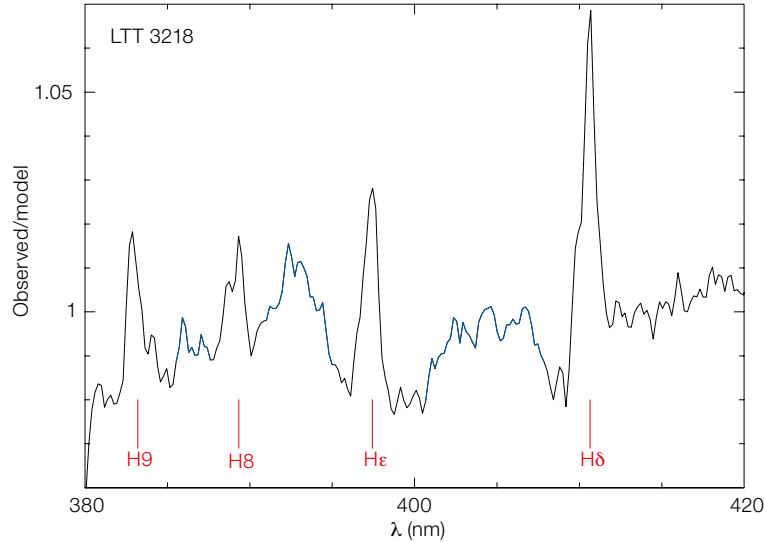
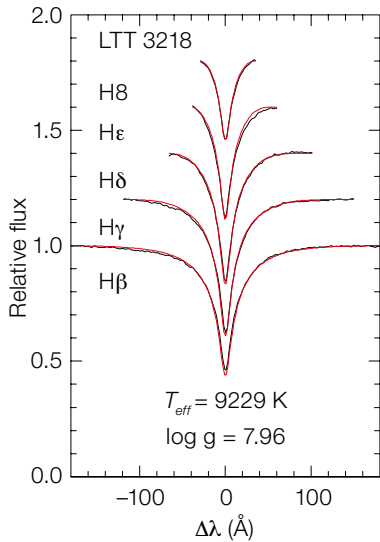


Figure 1. Left: Model fit for LTT 3218 from Giammichele et al. (2012) for individual H lines only (black lines mark observed spectrum; red lines the model). Right: Ratio between the observation and model spectrum, clearly showing residuals in the line cores (labelled) and also some bumps between the lines (marked in blue).

changes in these parameters. In consequence, this means that model spectra with an incorrect effective temperature or surface gravity will not correctly describe the strong hydrogen and/or helium absorption lines in the spectra of these stars. Such a mismatch is most severe at the blue end of the wavelength range studied in this paper, namely between 380 nm and 420 nm, where the lines may overlap with each other.

An example of such a mismatch can be seen in the right-hand panel of Figure 1, which shows the ratio of the observed to the fitted model spectrum for LTT 3218. The bumps at 390–395 nm and 400–410 nm are caused by an imperfect description of the line overlap region between the Balmer lines H8 (389 nm), Hε (397 nm) and Hδ (410 nm). Compared to the line depths of about 50%, the effects are small (about 2%), but sufficient to introduce noticeable artefacts in the resulting response curves. To ensure that no such mismatches exist in the finally selected reference spectra, however, the true response of the instrument with which the spectra were observed must be known.

This was the primary motivation to include the standard L97–3, whose featureless spectrum can easily be modelled

in the wavelength range discussed here. This is illustrated in Figure 2, which shows the ratio of the observed spectrum to model spectrum for L97–3 for the regions containing strong lines in the spectra of the flux standard stars discussed here. As reference data for this star, a stellar model spectrum (Koester 2010) calculated for the parameters reported by Giammichele et al. (2012) was employed. This model spectrum was adjusted to the published photometry of the star. The resulting response curve, shown in Figure 2, is rather smooth without significant structure on nanometre scales (as opposed to Figure 1).

X-shooter observations of the six standard stars were used to verify the quality of the various model spectra available for them by comparing instrumental response curves from different standard stars. We concentrated first on the wavelength range 380 nm to 440 nm for the reasons discussed above. Once an acceptable description of the blue range had been achieved, its suitability for the redder wavelength ranges was verified as well. One-dimensional extracted and merged X-shooter spectra of the flux standard stars, produced with the Reflex workflow¹ (Freudling et al., 2013), were used for this analysis. These spectra were then

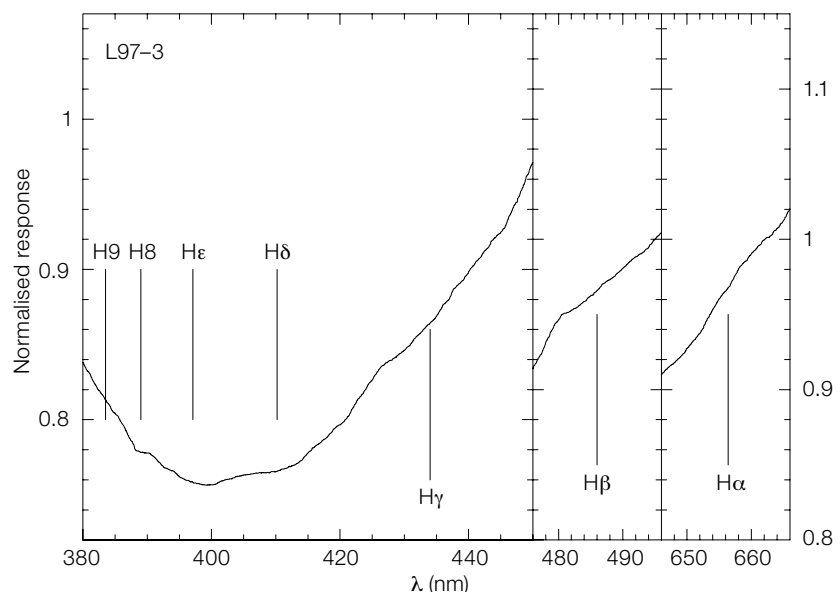


Figure 2. The average ratio of observed and shifted reference spectrum is shown for L97–3, for the same wavelength ranges as in Figure 3.

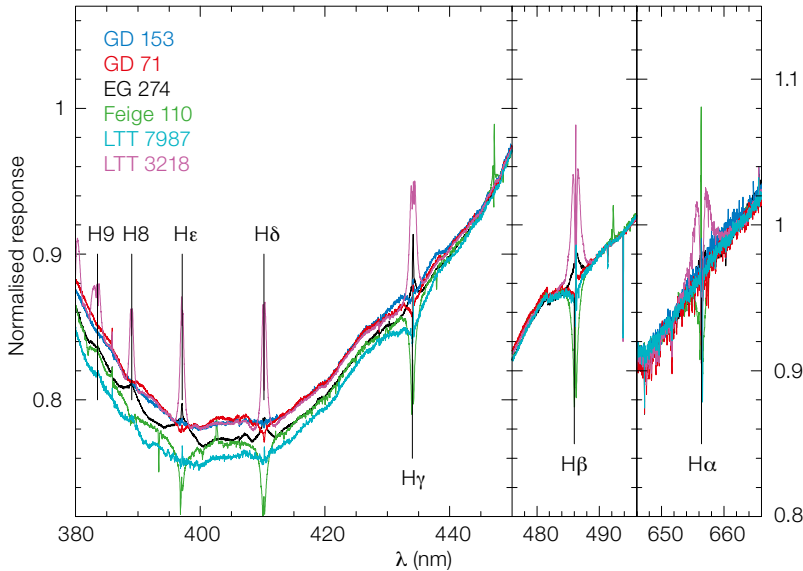


Figure 3. The average ratios of observed standard star spectrum (corrected for atmospheric extinction) and shifted reference spectrum, using the bump-corrected model spectra, are displayed. The curves have been normalised at 456 nm, 495 nm and

662.1 nm, respectively, and are offset in steps of 0.02 for better visibility. The positions of the Balmer lines are marked. Feige 110 in addition has helium lines and interstellar Ca II lines in its spectrum.

corrected for atmospheric extinction using the Paranal extinction curve and normalised by exposure time.

The model spectrum for a given star was aligned to the same radial velocity as the observed spectrum to avoid the introduction of pseudo-P Cygni profiles in the response. Each observed standard star spectrum was then divided by the shifted reference star spectrum. Finally the ratios were averaged per star to achieve a better signal-to-noise ratio. This provided raw, i.e., unsmoothed, response curves that allowed us to look for systematic discrepancies between the observed and the model spectra. Any feature in these ratios that does not appear for all standard stars points strongly towards deficiencies in the reference spectra, since instrumental effects should not depend on which standard star is used. We selected, as the best description of the stellar spectrum, those model spectra that showed the smallest star-specific bumps in the averaged ratio spectra between 380 nm and 440 nm.

In order to correct the remaining mismatches between observed and model spectra that cause bumps like those seen in Figure 1, the average raw response of

each star was divided by the smoothed response curve derived from L97-3 in order to remove instrument specific variations. The products of this procedure are expected to be equal to 1.0 in an ideal case, but differences in atmospheric conditions result in residual slopes. For every star the shape of this ratio spectrum was fitted by a low-order polynomial to remove the large-scale variations, the result smoothed and the remaining bumpy regions fitted. The fitted result was then applied to the model spectrum to provide the reference spectrum.

The bump corrections were smallest for GD 71, GD 153, and Feige 110, while EG 274, LTT 7987 and LTT 3218 had significant corrections (increasing in that order). This is expected as the last three stars have the strongest and widest lines and thus present the biggest challenge in the correct treatment of overlapping lines. Since the mismatches in the line cores were not corrected (they vary with spectral resolution), some masking is still required when fitting a response (see below). We also verified that, in the spectral range 440 nm to 2500 nm, the only residuals seen in the response curves are those in the line cores of hydrogen and/or helium lines.

Photometric calibration

We have now defined a set of model spectra which adequately reproduce the observed X-shooter spectra of the six flux standard stars, with residuals (outside the line cores which are affected by resolution effects) well below 2%. To allow for a proper flux calibration we have to verify that the overall flux distribution of these model spectra reproduces the independently observed (spectro-)photometric data. To do so the model spectra for EG 274, Feige 110, LTT 3218, and LTT 7987 between 300 nm and 1000 nm were convolved to a resolution of 1.6 nm and then binned into 5 nm steps to reproduce the tabulated data (Hamuy et al., 1992; 1994). For the NIR region, the model spectra were convolved to a resolving power of 2000 (*J*-band) and 1500 (*H*- and *K*-bands) and then integrated over the wavelength ranges given in Vernet et al. (2008). These flux values were then aligned to the respective (spectro-)photometric data by a constant factor across the full wavelength range. For GD 71 and GD 153 our new model spectra could also be aligned by a constant factor to the Hubble Space Telescope model spectra (Bohlin et al., 2001). Figure 3 shows the average ratios of the observed and reference spectra for the new model spectra.

Correction of telluric absorption

We have now defined reference spectra that describe the observed spectra of the flux standard stars very well. In order to derive a response curve, the effects of the Earth's atmosphere have to be removed from the observed spectra, otherwise the response curve will contain a mixture of instrumental and atmospheric effects. The atmospheric effects consist of two major parts: atmospheric extinction (small variation with time in the case of Paranal due to the low aerosol content, which governs the extinction variability); and telluric absorption (strong variation with time in the case of water vapour). The former affects mostly the wavelength range 300 nm to 1000 nm and is described by the Paranal extinction curve. The second is important for wavelengths above 600 nm and may vary on very short timescales.

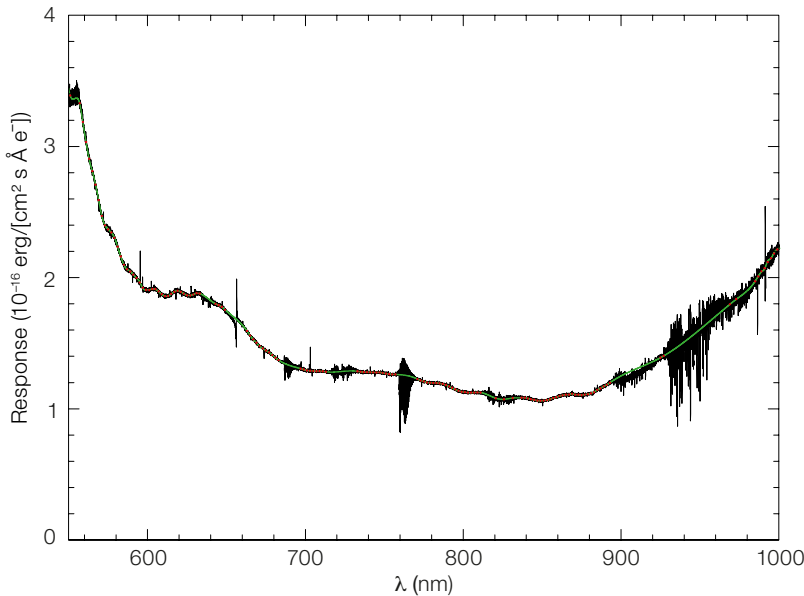


Figure 4. X-shooter response curve derived for EG 274 (VIS arm). The red dots mark the fit points and the green line the fit through these points.

Unless at least those parts of the spectrum that contain low-to-medium strength telluric absorption features are corrected, the response has to be interpolated across very wide wavelength ranges, resulting in large systematic uncertainties for the resulting flux calibration. Traditionally such corrections use telluric standard stars, i.e., stars with either no features or extremely well-known features in the regions of telluric absorption, which allow the user to determine the intrinsic telluric absorption spectrum. This method relies on the assumption that the conditions governing telluric absorption have not changed between the observation of the science target and the observation of the standard star. Since this assumption is often not fulfilled, it was decided instead to use a catalogue of telluric model spectra (Noll et al., 2012) in order to correct the telluric absorption lines.

High resolution atmospheric transmission spectra ($R = 60\,000$) were calculated for the wavelength range from 300 nm to 30 μm using the line-by-line radiative transfer model code (LBLRTM; Clough et al., 2005), the High resolution TRANmission molecular line database (HITRAN; Rothmann et al., 2009), and dif-

ferent average atmospheric profiles (pressure, temperature and molecular abundances) appropriate for Cerro Paranal.

To identify the telluric model spectrum best suited to correct a given observation, the telluric model spectra first have to be aligned to the observed spectrum in both resolution and wavelength. Then the telluric model spectrum with the smallest residuals with respect to the observation has to be identified. The following procedure was employed. Firstly the wavelength scale (in nm) of the model and observed spectra were converted to natural logarithm, because X-shooter has a constant resolving power. (For instruments with a constant full half width at half maximum with wavelength [FWHM], the procedure described below should be done in linear wavelength space.) An appropriate wavelength range of the telluric model spectra and observed spectra was then cross-correlated to determine the shift in wavelength and the difference in resolution. The telluric model spectrum was shifted and convolved with a Gaussian with the measured FWHM of the correlation peak. (Since the resolution of the observed spectra is about a factor of ten lower than the resolution of the telluric model spectra, it is assumed

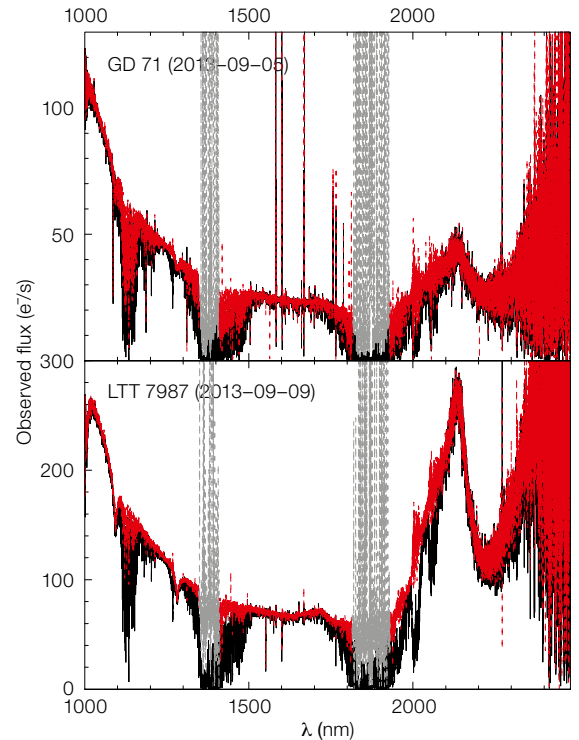


Figure 5. Results of the telluric correction (red) for a bad case (upper) and a good case (lower) are shown. Regions of extremely high telluric absorption have extremely high noise in the corrected data and are therefore omitted (1348–1410 nm, 1815–1930 nm). The lines at 1093.5 nm and 1281.4 nm are stellar lines and the variable peak at about 2100 nm is caused by variations in the flux level and spectral energy distribution of the flat field lamp.

here that the resolution of the model spectra is infinite.) Finally, the shifted and convolved telluric model spectrum was converted back to linear wavelength space. The observed spectrum was then divided by the adjusted telluric model spectrum and normalised by a cubic spline fit using predefined continuum points (avoiding regions of strong telluric absorption as well as known lines of the observed star).

The best-suited telluric model spectrum was chosen as the one for which the average residuals computed over regions of moderate telluric absorption in the normalised telluric-corrected stellar spectrum are minimal. Figure 5 shows examples of good telluric correction (lower) and of undercorrection (upper). The telluric-corrected spectrum of the flux standard star is then compared to the stellar model spectrum to determine the response.

Users who wish to employ the telluric model spectra to correct their data can find information about the Cerro Paranal sky model (Noll et al., 2012) on the skytools webpage² together with pre-calculated libraries³. The spectra are provided with resolutions of 60 000 and 300 000 and do not include Rayleigh scattering. The SkyCalc web application⁴ can always be used to produce sky radiance and transmission spectra with more specific parameters, including Rayleigh scattering.

Fitting of the response

The ratio of the observed spectrum to the shifted reference spectrum usually shows residuals at the positions of the line cores (see Figure 3), but may also show variations on intermediate wavelength scales that need to be fitted by the response curve because they are instrumental features. In the case of X-shooter we found that the best solution was a spline fit to a list of wavelengths per star, where the median of the raw response across a pre-defined window is determined at each listed wavelength (see Figure 4 for an example). Also the quality of the telluric correction has to be kept in mind when fitting a response, as regions with remaining absorption or overcorrected features may distort the fit. For this reason we finally decided to mask certain regions affected by telluric absorption when fitting a response curve, in order to avoid potential telluric residuals (see Moehler et al. [2014] for details). We would like to emphasise that even with this masking far less of the spectrum is rejected than would be necessary if no telluric correction had been applied.

Final remarks

To illustrate the quality that can be achieved with the methods and model spectra described in this paper, we show in Figure 6 an example for a standard star (LTT 7987). The spectrum was flux-calibrated with the response curve determined from a different star observed on the same night, namely EG 274. Part of the response curve used for this calibration is shown in Figure 4.

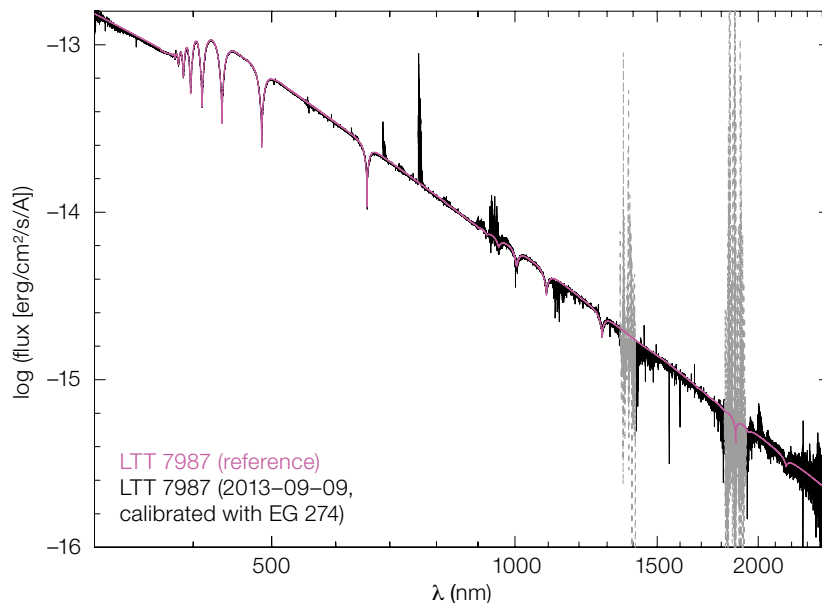


Figure 6. Spectrum of LTT 7987, corrected for telluric absorption and flux-calibrated with a response curve derived from observations of EG 274. The

magenta curve is the reference spectrum for LTT 7987. Regions of very high telluric absorption are omitted (1348–1410 nm, 1815–1930 nm).

While the set of standard stars is adequate to flux calibrate spectra observed in the southern hemisphere, additional standards would be useful both to enlarge the number of potential calibrators in the south, and to provide a similar set of standards in the northern hemisphere. The methodology described here can be used to derive such a set of model spectra. Necessary ingredients for such an endeavour are accurate model spectra, availability of flux information, and observed uncalibrated spectra for both the new calibrators and at least one of the standard stars discussed here to correct for instrumental features. For hot (pre-) white dwarfs, like the flux standard stars discussed here, and many others, a good starting point for model spectra would be the TMAP spectral energy distribution available from the registered Virtual Observatory service TheoSSA⁵ provided by the German Astrophysical Virtual Observatory⁶.

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References

- Bergeron, P., Saffer, R. A. & Liebert, J. 1992, *ApJ*, 394, 228
- Bohlin, R. C., Dickinson, M. E. & Calzetti, D. 2001, *AJ*, 122, 2118
- Clough, S. A. et al. 2005, *J. Quant. Spectrosc. Radiat. Transfer*, 91, 233
- Freudling, W. et al. 2013, *A&A*, 559, A96
- Giammichele, N., Bergeron, P. & Dufour, P. 2012, *ApJS*, 199, 29
- Hamuy, M. et al. 1992, *PASP*, 104, 533
- Hamuy, M. et al. 1994, *PASP*, 106, 566
- Koester, D. 2010, *MmSAI*, 81, 921
- Moehler, S. et al. 2014, *A&A*, 568, A9
- Noll, S. et al. 2012, *A&A*, 543, A92
- Rothman, L. S. et al. 2009, *J. Quant. Spectrosc. Radiat. Transfer*, 110, 533
- Vernet, J. et al. 2008, *SPIE*, 7016, 70161G

Links

- ¹ Reflex X-shooter workflow: <http://www.eso.org/sci/software/pipelines/>
- ² Cerro Paranal sky model: <http://www.eso.org/sci/software/pipelines/skytools/>
- ³ Library for calculation of model sky: ftp://ftp.eso.org/pub/dfs/pipelines/skytools/telluric_libs
- ⁴ SkyCalc web application: <http://www.eso.org/observing/etc/skycalc/skycalc.htm>
- ⁵ TMAP spectral energy distributions: <http://dc.g-vo.org/theossa>
- ⁶ GAVO: <http://www.g-vo.org>