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Stellar Atmospheric Parameters from Full Spectrum Fitting of Intermediate- and High-resolution Spectra against PHOENIX/BT-Settl Synthetic Stellar Atmospheres

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Abstract. We present a new technique implemented in IDL for determination of the parameters of stellar atmospheres using PHOENIX and BT-Settl synthetic stellar spectra. The synthetic spectra provide good coverage in the $T_{\rm eff}$, log(g), [Fe/H], [α/H] parameter space over a wide wavelength range and allow fitting observed spectra of a vast majority of stars. Our procedure also determines radial velocities and stellar rotation and it takes into account flux calibration imperfections by fitting a polynomial continuum. Thanks to using pixel fitting we can exclude certain spectral features which are not present in the models such as emission lines (chromospheric emission in late-type stars or discs around Be stars). We perform a non-linear χ^2 minimization with the Levenberg-Marquardt method that is applied to the entire spectrum with the exception of areas with peculiarities: emission lines, model shortcomings (incompleteness of the spectral line lists used for the atmospheric model calculation). We compare the results of the analysis of optical spectra from ELODIE and INDO-US stellar libraries.

1. Introduction

The analysis of galaxy spectra has been historically performed using stellar population models which can be constructed in different ways. One can model stellar populations using synthetic stellar atmospheres which can be calculated for an arbitrary range in the $T_{\rm eff}$, log(g), [Fe/H] and [α/H] parameter space. The obvious drawback of this approach is that the list of spectral lines is never complete which means that stellar population model will inherit missing lines and will be discrepant with real galaxy spectra. On the other hand stellar populations modeled using observed stellar spectra match real galaxy spectra substantially better but observed spectra of stars used for modeling always cover a smaller region of the parameter space compared to synthetic spectra and are subject to imperfections in data reduction and calibration or a given star itself may be peculiar.

These problems can be partially solved by the use of semi-empirical models of stellar populations. These models are based on spectra from empirical stellar libraries complemented with synthetic spectra in the regions of the parameter space not well covered by empirical spectra. It is crucially important to accurately determine stellar atmospheric parameters of observed stars in order to correctly combine empirical and the synthetic grids of stellar spectra. Our work addresses the latter problem by using full spectrum fitting.

2. Pre-processing of Spectral Libraries

In this work we used PHOENIX (Husser et al. 2013) and BT-Settl (Allard et al. 2013) libraries of synthetic stellar atmospheres and INDO-US (Valdes et al. 2004), ELODIE (Prugniel et al. 2007), and UVES-POP (Bagnulo et al. 2003) empirical libraries of stellar spectra. For the parameter determination of stellar atmospheres we have prepared several grids of synthetic stellar spectra based on PHOENIX and BT-Settl libraries in order to cover a large range of parameters. We complemented the PHOENIX library at the high-temperature end ($T_{eff} > 15000$ K) by BT-Settl spectra, convolved them to the desired spectral resolution values and kept the two versions of each grid in vacuum and atmospheric wavelengths (Morton 2000). We generated a set of such synthetic grids for every value of the abundance of α-elements available in Phoenix ([α/H] = −0.4, −0.2, 0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2 dex). As a result we have constructed grids of synthetic stellar spectra at spectral resolutions $R = 5000$, 10000, and 20000 in the wavelength range from 300 nm to 2.5 μm in a very wide range of atmospheric parameters (T_{eff}: 2300 . . . 70000 K, log(g): −0.5 . . . 6.5, [Fe/H]: −4.0 . . . 1.0 dex, [α/H]: −0.4 . . . 1.2 dex).

The preparation of empirical libraries of stellar spectra included post-processing of every individual spectrum. The INDO-US library ($R = 5000$) was fully re-assembled and re-calibrated in flux. We applied the telluric correction procedure developed for MagE data reduction pipeline, then ran a procedure for stitching non-intersecting spectral setups which used the model approximation, determined spectral line-spread function (LSF), corrected global imperfections of continua, and determined masks of poorly modeled spectral lines in several bins by T_{eff}. For the ELODIE spectra, we determined the LSF, corrected the continuum, and also calculated the line masks at $R = 10000$. The UVES-POP stellar spectra library required complete re-reduction of the original data using a new version of the UVES pipeline with adhoc correction for diffuse light and Echelle order stitching. We reduced its resolution to $R = 20000$. The entire process was briefly described in Borisov et al. (2018).

3. Description of the Spectrum Fitting Technique

The core of our method is a multidimensional interpolation procedure which produces a synthetic spectrum for any set of stellar atmospheric parameters and a non-linear minimization technique. At input, it requires a regular grid of spectra, for example, the one we described above in Section 2 which then undergoes the multi-dimensional spline interpolation and then is used in a non-linear χ^2 minimization using the Levenberg-Marquardt method (Markwardt 2009). During the minimization, in addition to the three parameters of stellar atmospheres (T_{eff}, log(g), [Fe/H] for a fixed value of [α/H]), the procedure also calculates a global radial velocity and the projection of a rotational

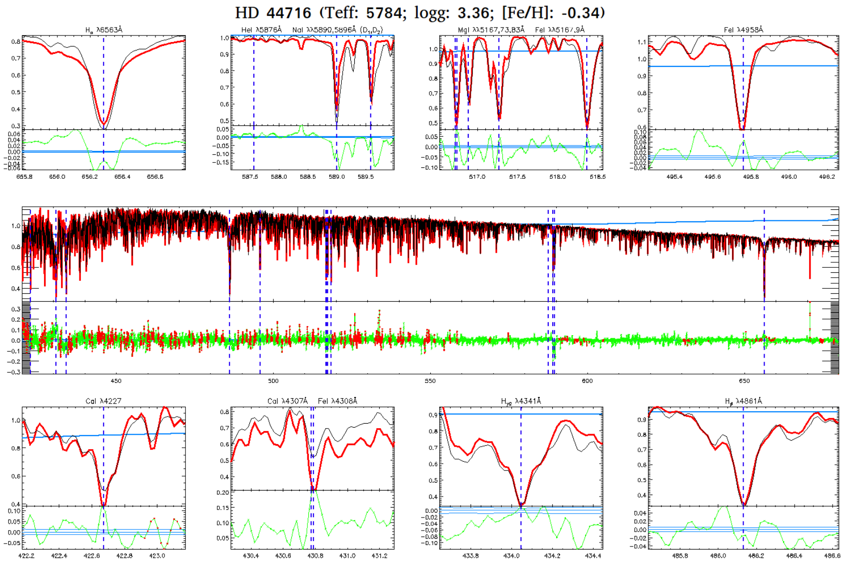

Figure 1. Application of our spectrum fitting technique to HD 44716 from the ELODIE library. Central panel shows the observed spectrum in black the best-fitting model in red and fitting residuals in green with masked regions shown in red. Smaller panels zoom in on the profiles of several spectral lines.

velocity of a star ($v \sin(i)$). Optionally we can account for residual wavelength calibration errors using a low-order polynomial function. Because the global continuum of an empirical spectrum is subject to flux calibration errors we correct it with a low-order Legendre polynomial in order to bring a spectrum closer to the model. The observed spectra may possess some features that are not well modeled in synthetic spectra, for example, some spectral lines coming from chromospheric emission or interstellar absorption, also data reduction imperfections like cosmic ray hits, etc. In order to ensure that such artifacts are not affecting the minimization we construct masks that exclude these spectral regions. At the end our procedure performs the χ^2-minimization over the entire spectrum excluding the masked regions with pixel weights inversely proportional to flux uncertainties. An example of our technique applied to a stellar spectrum is shown in Fig. 1. The code is written in *IDL* using *MPFIT* and *LAPACK* packages. It allows us to fix and/or tune all components of the fitting procedure. We plan to re-write the code into *Python* in the near future and make it publicly available.

4. Comparison of the Fitting Results for Spectra from Different Stellar Libraries

We tested our approach using Monte Carlo simulations which showed excellent convergence and independence of the solution from the initial guess. We then applied our technique to observed stellar spectra from the stellar libraries ELODIE (1959 spectra reduced to $R = 10000$), INDO-US (1273 spectra, $R = 5000$) and UVES-POP (408 spectra, reduced to $R = 20000$) at wavelengths longer than 420 nm. To determine the parameters of stellar atmospheres the spectra of each library were corrected for a global continuum. We used pixel masks created for each library as described earlier.

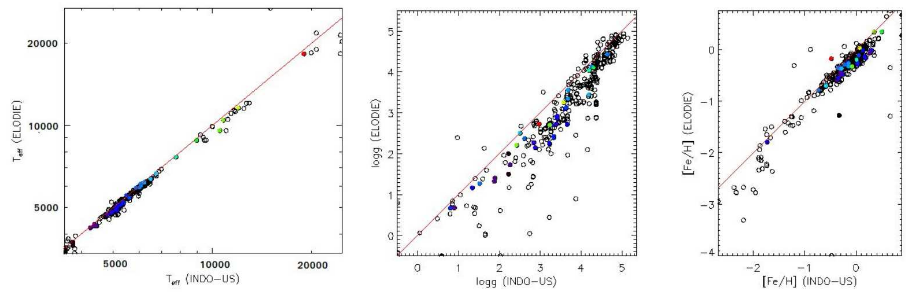

Figure 2. Comparison of the fitting results between ELODIE and INDO-US stellar libraries. The panel left to right shows a comparison of effective temperature, surface gravity, and metallicity. Empty circles show all cross-matched stars between ELODIE and INDO-US (408 spectra). Colored circles show the subset of stars for which CDS Simbad reports the object type '*' (35 spectra).

We compare the derived atmospheric parameters for the overlapping sub-sample of stars in the ELODIE and INDO-US stellar libraries (Fig. 2). In general, there is a good agreement between the fitting results for effective temperature and metallicity for the full sub-sample. There is a slight systematic difference in log*g* values which might be the result of using different fitting wavelength ranges for the two stellar libraries, because the quality of synthetic stellar spectra changes across wavelengths. Some stars can also be discrepant because of spectral binarity and/or variability.

Our method allows us to determine the stellar atmospheric parameters for the stellar spectra of all spectral classes and metallicities within the framework of synthetic grids. For each spectrum individual fine tuning of the fitting parameters is possible. Accounting for the polynomial continuum allows one to account for flux calibration imperfections that distort the global continuum shape. The construction of pixel masks eliminates features badly modeled in synthetic atmospheres and data reduction artifacts in the observed spectra. All this together allows us to determine parameters of stellar atmospheres with the accuracy sufficient for stellar population modeling.

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