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Automated Spectral Analysis

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Abstract. We describe model atmosphere and synthetic spectrum fitting software used for the semi-automatic analysis of a wide range of stellar spectra, and provide examples of their application. Our goal is to provide robust tools for the automatic analysis of high-quality datasets observed with multi-object spectrographs on large telescopes.

1. Introduction

In about 1814 Joseph Fraunhofer made a hand-coloured drawing of the solar spectrum in which he showed 574 dark absorption lines and demonstrated the visible solar flux distribution. This contrasts starkly with today's capacity to obtain high-fidelity high-resolution spectra of hundreds of faint stars simultaneously. Theoretical understanding of the physical processes that lead to the formation of a stellar spectrum is such that information may now be deduced that was unimaginable two centuries ago. However, the extraction of that information is rarely trivial and is too often handicapped by manual techniques. It is now necessary to examine means to automate the process of spectral analysis.

2. Theoretical models

The background to this work lies in the legacy of UK Collaborative Computational Project No. 7 for the Analysis of Astronomical Spectra (Jeffery 1996). In connection with this project, the author and others have built up a collection of software for the calculation of stellar atmospheres and synthetic spectra, including libraries of atomic data. This is illustrated by the evolution of a stellar atmosphere code *STERNE* originally written by Schönberner & Wolf (1974), augmented by opacity distribution functions (Kurucz 1979), and new continuous opacities from the Opacity Project (Seaton et al. 1994). Much code has been rewritten in order to share source with the formal solution code *SPECTRUM* of Dufton et al. (unpublished), which has been similarly enhanced through the last decade. An assessed atomic database for modelling lines in early-type stars has also been developed *LTE_LINES* (Jeffery 1991). The combination (Jeffery, Woolf & Pollacco 2001) now routinely provides high-quality synthetic spectra for early-type stars assuming a plane-parallel atmosphere in hydrostatic, radiative and local thermodynamic equilibrium for a range of assumed compositions.

In order to address several problems, a substantial grid of model atmospheres and synthetic spectra has been constructed. These cover a range of

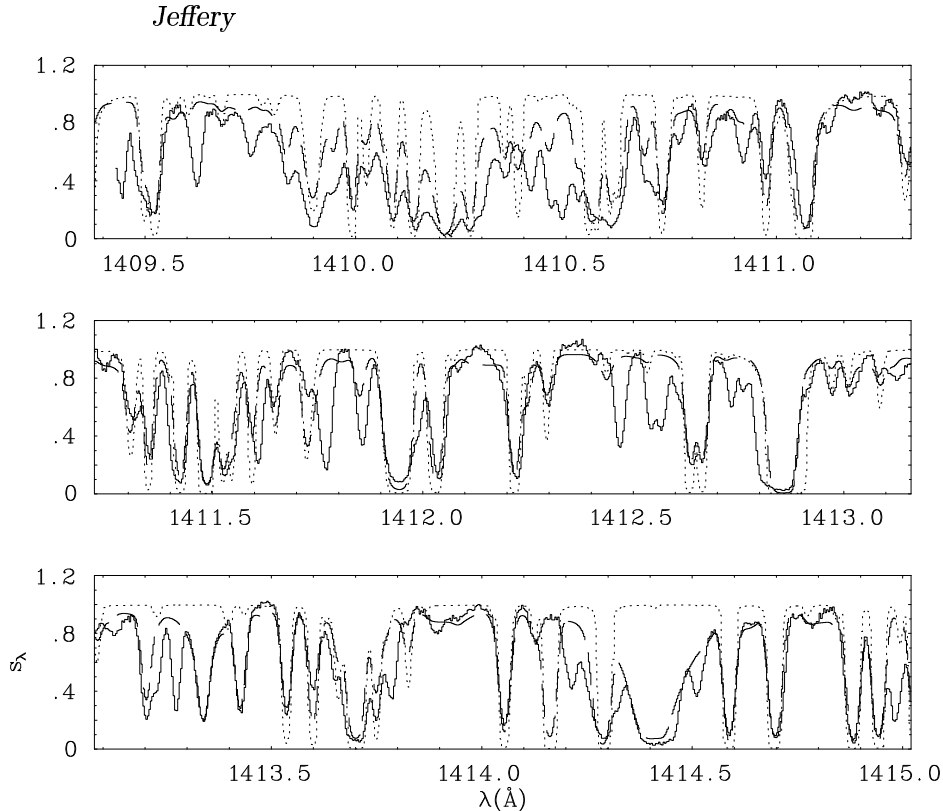


Figure 1. Comparison of the HST GHRS spectrum of χ Lup (solid), the best-fit model (broken) computed by Leckrone et al. (1999) and a model computed with SPECTRUM (dotted).

helium abundance ($n_{\text{He}} = 0.001 - 0.999$), effective temperature ($T_{\text{eff}} = 10\,000 - 50\,000$ K), and surface gravity ($\log g = 1.0 - 7.0$). With $> 2\,500$ models, the grid includes high-resolution spectra in spectral ranges $3900 - 5000$ and $6000 - 7000$ Å. The database, which is available on the internet, includes the model structures, broad-band flux distributions, and emergent, continuum and normalized spectra. Tests of these codes against both theoretical (SYNSPEC: Hubeny & Lanz 1995) and observed spectra (χ Lup: Leckrone et al. 1999) are satisfactory, pointing principally to differences in the atomic data used in each case (Fig. 1).

3. Spectral Fitting

Our problem is to find the set of parameters which describe the model which best fits an observed spectrum. This may be expressed in terms of either an observed broad-band flux distribution F_{λ} or a normalized high-resolution spectrum $S_{\lambda} = F_{\lambda}/F_c$. The theoretical equivalents (f_{λ} , s_{λ}) are functions of parameters defining the star, convolved with functions defining the observations. Adopting conventional notation for the stellar parameters, we then have:

$$\phi_{\lambda}(T_{\text{eff}}, \theta, E_{\text{B-V}}) = \theta^2 f_{\lambda}(T_{\text{eff}}, [\log g, n_i, i = 1, \dots]) A_{\lambda}(E_{\text{B-V}})$$

$$s_{\lambda}(T_{\text{eff}}, \log g, v_t, n_i, i = 1, \dots) = \phi_{\lambda}/\phi_c = f_{\lambda}/f_c$$

In our analyses we have had to consider the convolution of s with some or all of instrumental broadening (I), rotational broadening (V), acceleration during an exposure (A), and projection of an expanding photosphere into the line of sight P (Montañes Rodríguez & Jeffery 2001),

$$s'_\lambda = s_\lambda \otimes I(\Delta\lambda) \otimes V(v_{\text{rot}} \sin i) \otimes A(\delta v) \otimes P(v - \bar{v})$$

Thus f and/or s' represent functions of several parameters which are to be found by minimizing one of

$$\chi^2 = \Sigma_\lambda \frac{(F_\lambda - \phi_\lambda)^2}{\sigma_\lambda^2}, \chi^2 = \Sigma_\lambda \frac{(S_\lambda - s'_\lambda)^2}{\sigma_\lambda^2},$$

We also consider the case of binary stars where flux or lines from two stars with different sets of parameters contribute to the function to be fitted.

Multi-parameter fitting methods have been explored for stellar spectral analysis by a number of groups. The *Levenburg-Marquardt* method (Press et al. 1989) is an efficient procedure which uses second derivatives to estimate the location of the χ^2 minimum and has been used extensively elsewhere. In the *Downhill Simplex Method* (Press et al. 1989), a self-modifying cell (AMOEBAs) “oozes” across the χ^2 surface until a minimum is located. Because of non-linearity, *inversion techniques* which attempt to recover the structure of the atmosphere directly from the spectrum are only likely to be useful for extremely high quality data. On the other hand, *neural networks* are more promising and are being explored by several groups.

The Armagh fitting code currently comes in three flavours (Jeffery et al. 2001a). FFIT and SFIT operate on observables F and S respectively by interpolation in precomputed grids of f_λ and s_λ , using AMOEBAs as the χ^2 minimizer. A Levenburg-Marquardt minimizer is also available. In order to solve for abundances of individual atomic species, SFIT_SYNTH assumes that the principal parameters (T_{eff} , $\log g$, n_{He} , $[\text{Fe}/\text{H}]$) are known. $s_\lambda(v_t, n_i, i = \dots)$ is computed directly from an assumed model atmosphere, and χ^2 is used to deduce best values for microturbulent velocity and/or individual atomic abundances. In addition, we have made experimental use of the neural network code STATNET (Bailer-Jones et al. 1997).

All new code is written in FORTRAN 95 and the design is modular and flexible so that, for example, the spectrum generator may easily be substituted by a non-LTE formal solution code or, possibly, by a model atmosphere generator.

In practice, effort is required to tune the parameter search algorithm for a given dataset. Once optimized, it generally works well for datasets that are similar in spectral resolution, range and stellar type. The goal is to automate the derivation of astronomical information from large homogeneous datasets. Difficulties are encountered in three areas. i) The measurement of interstellar reddening from the $\lambda 2175$ Å absorption feature is not always successful. Non-standard reddening and the presence of substantial stellar iron-line absorption can lead an automatic procedure to find degenerate solutions. ii) Photon noise introduces small-scale structure in global minima which can fool the χ^2 minimizer. iii) Continuum estimation is complicated by line blending, multi-order spectrographs and non-linear optics.

4. Examples

The fitting software has been used successfully in several applications including the analysis of low-, intermediate and high-dispersion multi-wavelength data for extreme helium stars and subdwarf B stars, including binaries. Key results have led to the detection of secular contraction and the direct measurement of masses in extreme helium stars (Jeffery et al. 2001b). This has been pivotal in identifying extreme helium stars as the product of mergers between CO and He white dwarfs. A time-resolved analysis of the short-period pulsator V652 Her involved the automatic measurement of effective temperatures and surface gravities from over 50 high-dispersion optical spectra (Jeffery et al. 2001a). Semi-automatic techniques are even more important for the analysis of binary stars (Aznar Cuadrado & Jeffery 2001, 2002), including the discovery of a new hydrogen-deficient binary, BILyn (Jeffery & Aznar Cuadrado 2001) While our techniques have been developed using LTE models, it is likely that the efficiency gains will be even greater when extended to non-LTE models.

5. Future

In due course, the automatic spectral fitting software will become more robust and will be integrated with other software to enable the exploration of very large datasets (Jeffery: these proceedings). The goal is to accelerate the passage from the acquisition of astronomical spectra to advances in astrophysics.

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