Yunnan/Beijing 2019

Stellar Atmospheres

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2. The Line Profile

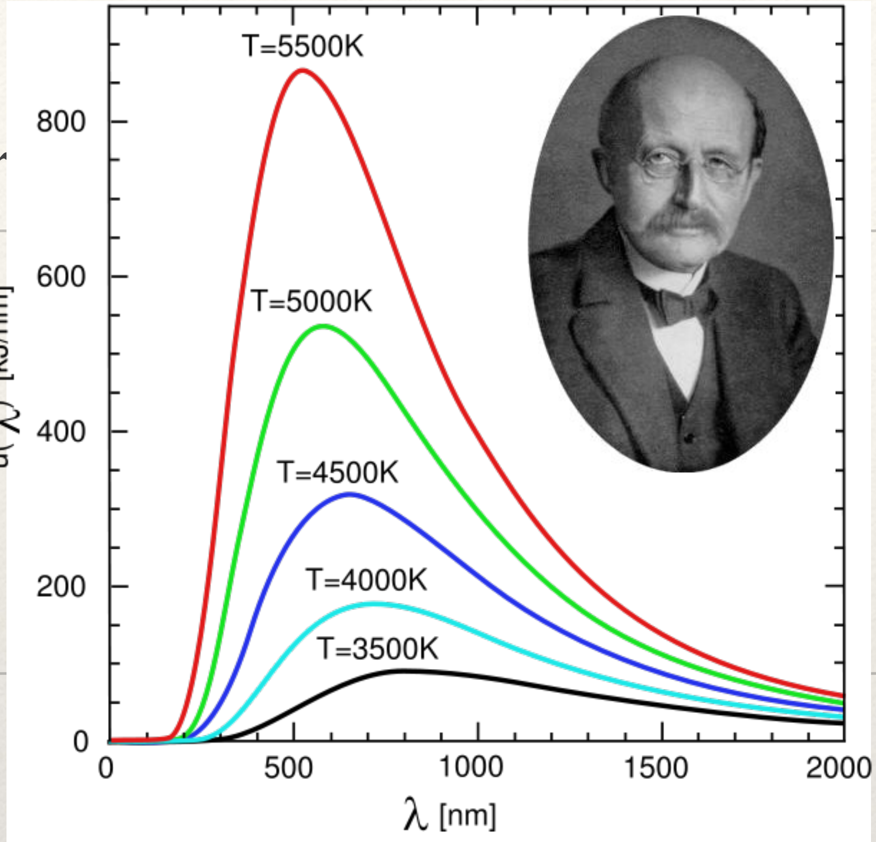
Programme

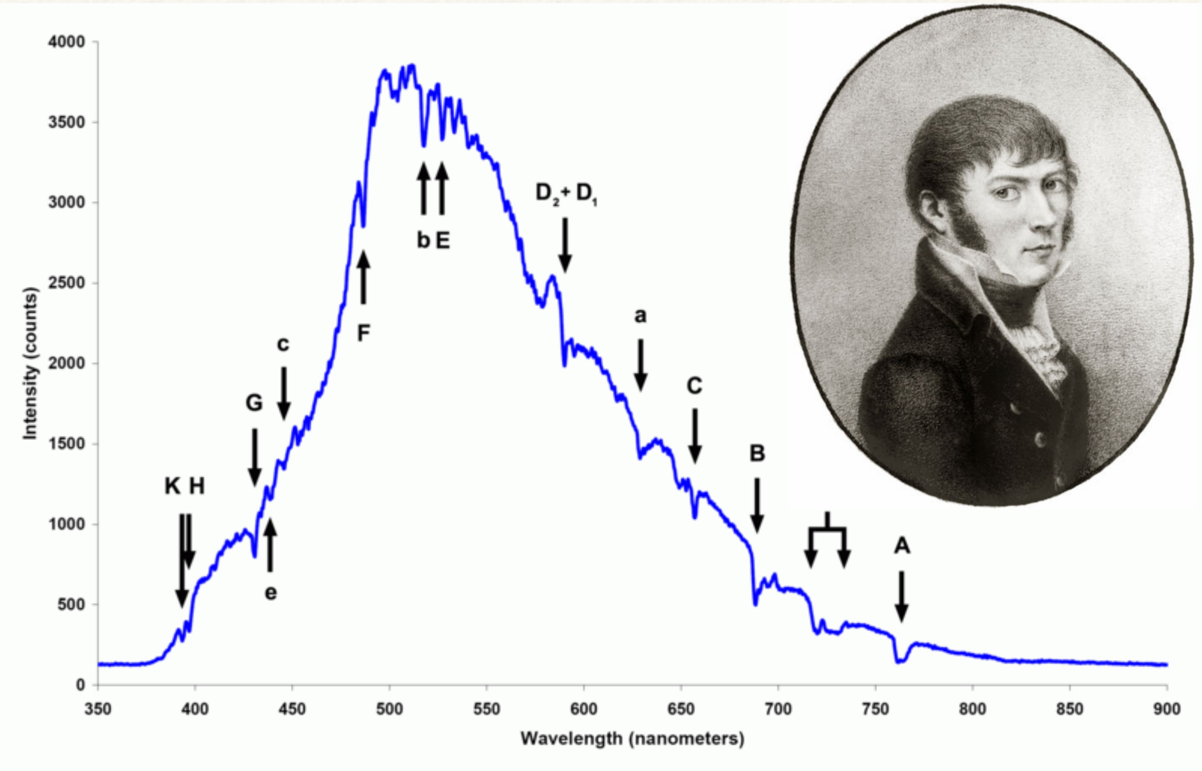
1. The Model Atmosphere
2. The Line Profile
3. Spectral Analysis

Stellar Atmospheres

1894: Max Planck

1814: Joseph von Fraunhofer





- Stellar interior: radiation in full LTE is “grey”: obeys Planck’s law
- Stellar surface: radiation obeys Kirchoff’s laws
- Absorption lines governed by number of ions and density of electrons
- A “model atmosphere” allows the emergent radiation to be compared with the observed spectrum.

.1. Spectral Diagnostics

Total flux distribution

T_{eff}: effective temperature

$E_{\mathrm{B-V}}$: extinction

θ: angular radius

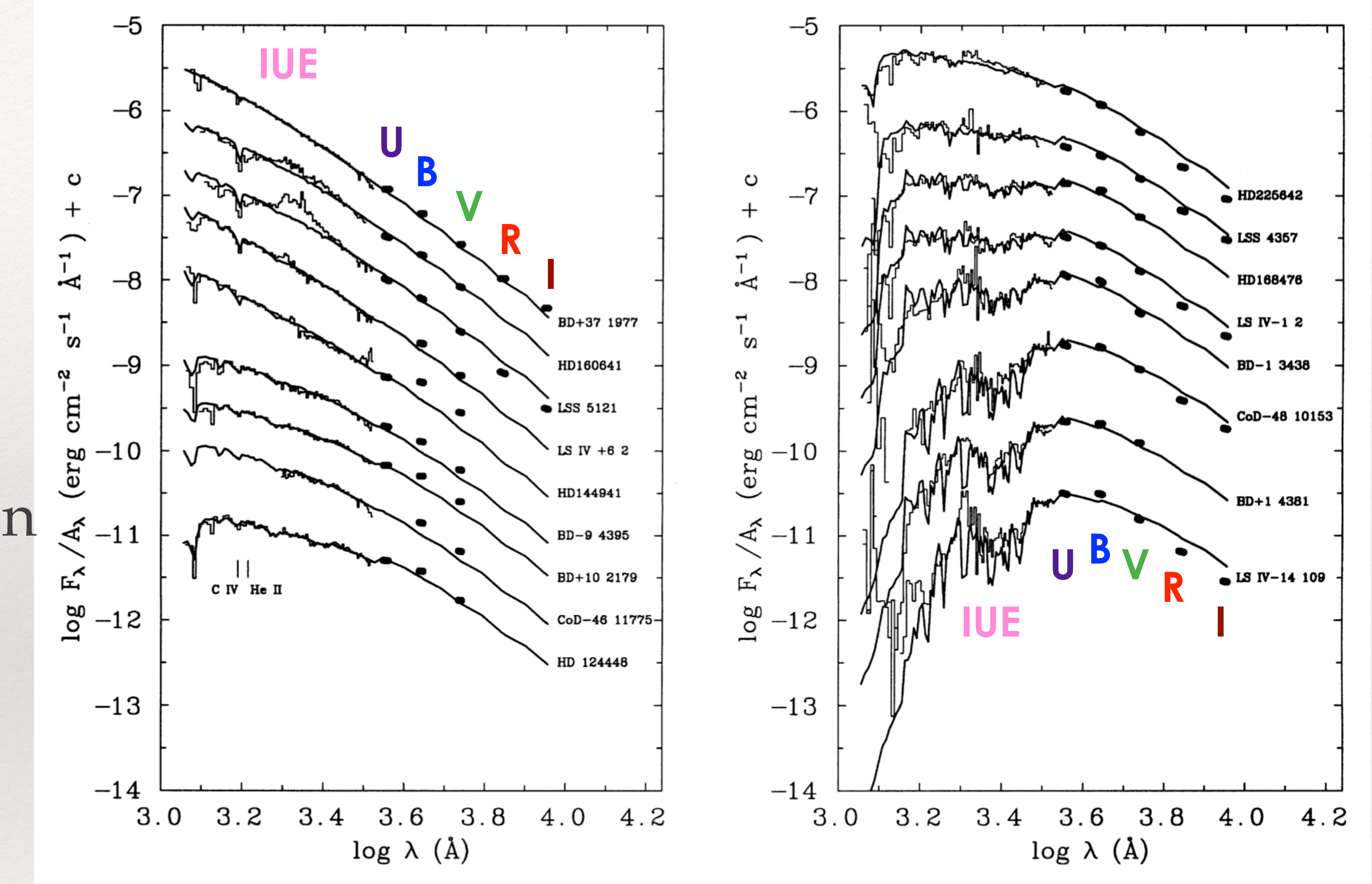
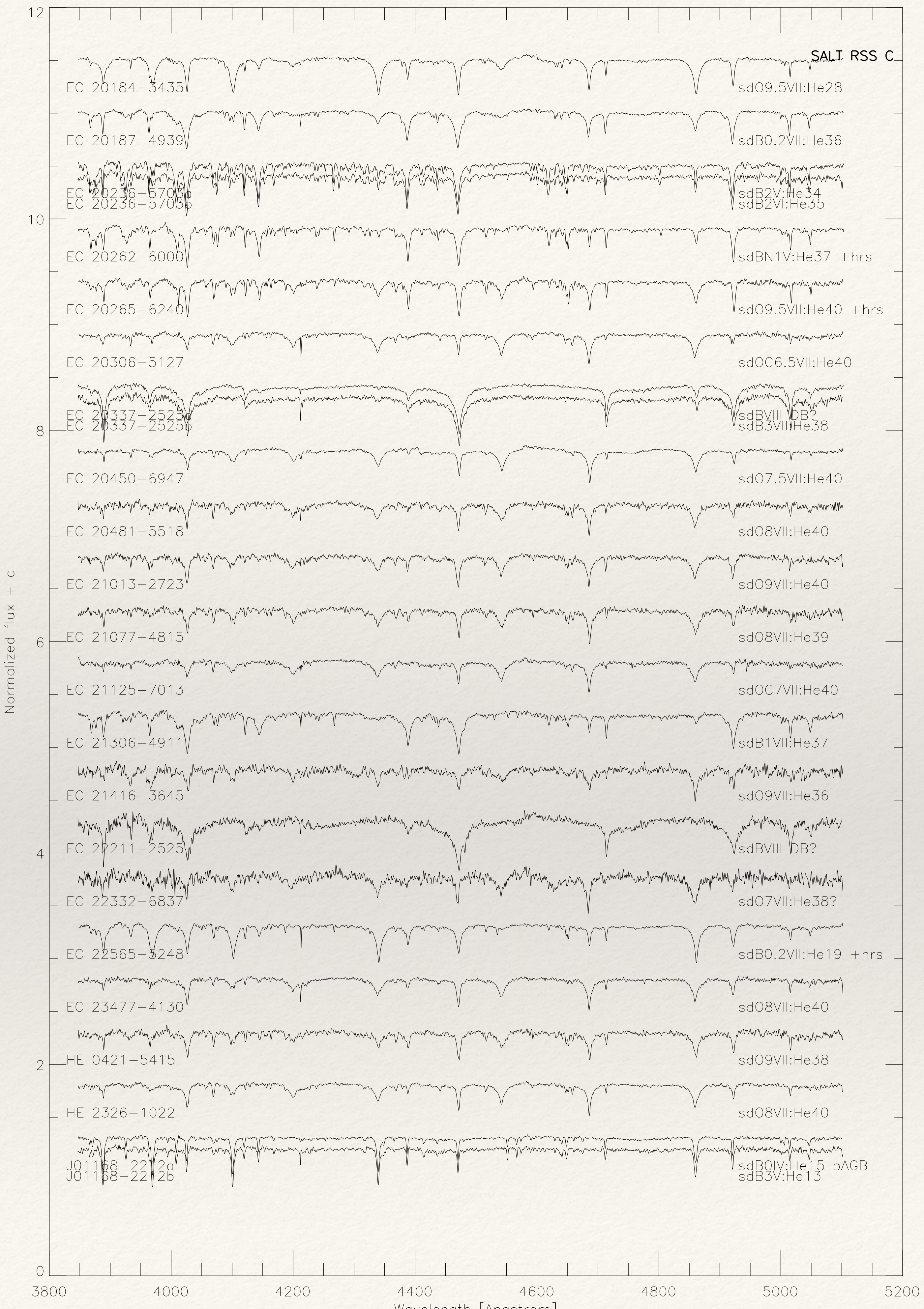


Figure 2. One SW/LW pair of *IUE* spectra for each programme star, binned to the resolution of the model atmosphere grid (thin histogram), together with the photometry from Table 3 (solid points), is compared with the theoretical flux distributions (thick curve) that best fit the *IUE* spectra. The spectra have been dereddened by the amount shown in Table 4 and multiplied by an arbitrary constant. The *IUE* and model spectra correspond to the last entry for each star in Tables 1 and 4.

.1. Spectral Diagnostics

Major absorption lines

T



.1. Spectral Diagnostics

Major absorption lines

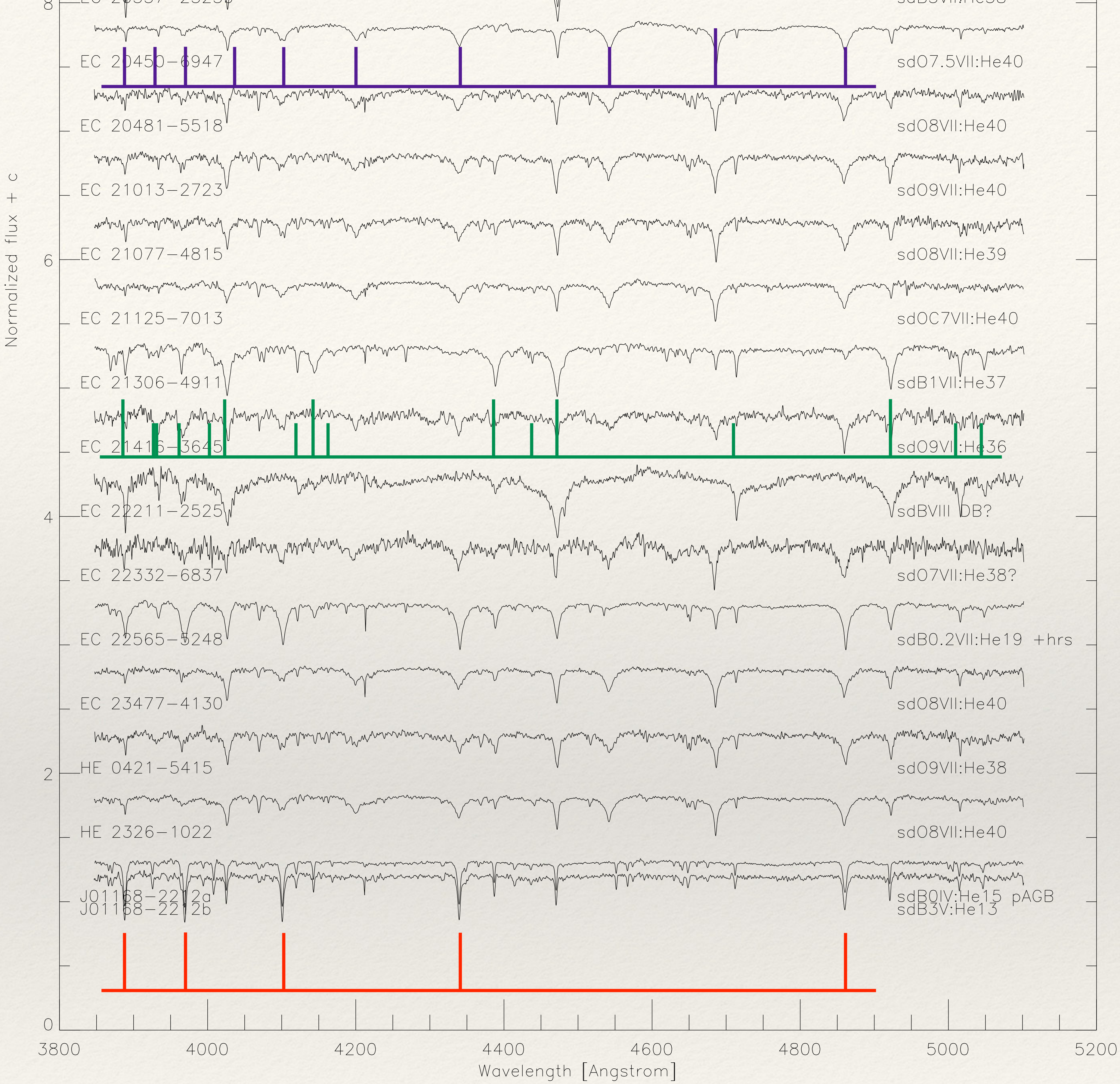
T_{eff}: effective temperature

g: surface gravity

[He/H]: helium / hydrogen ratio

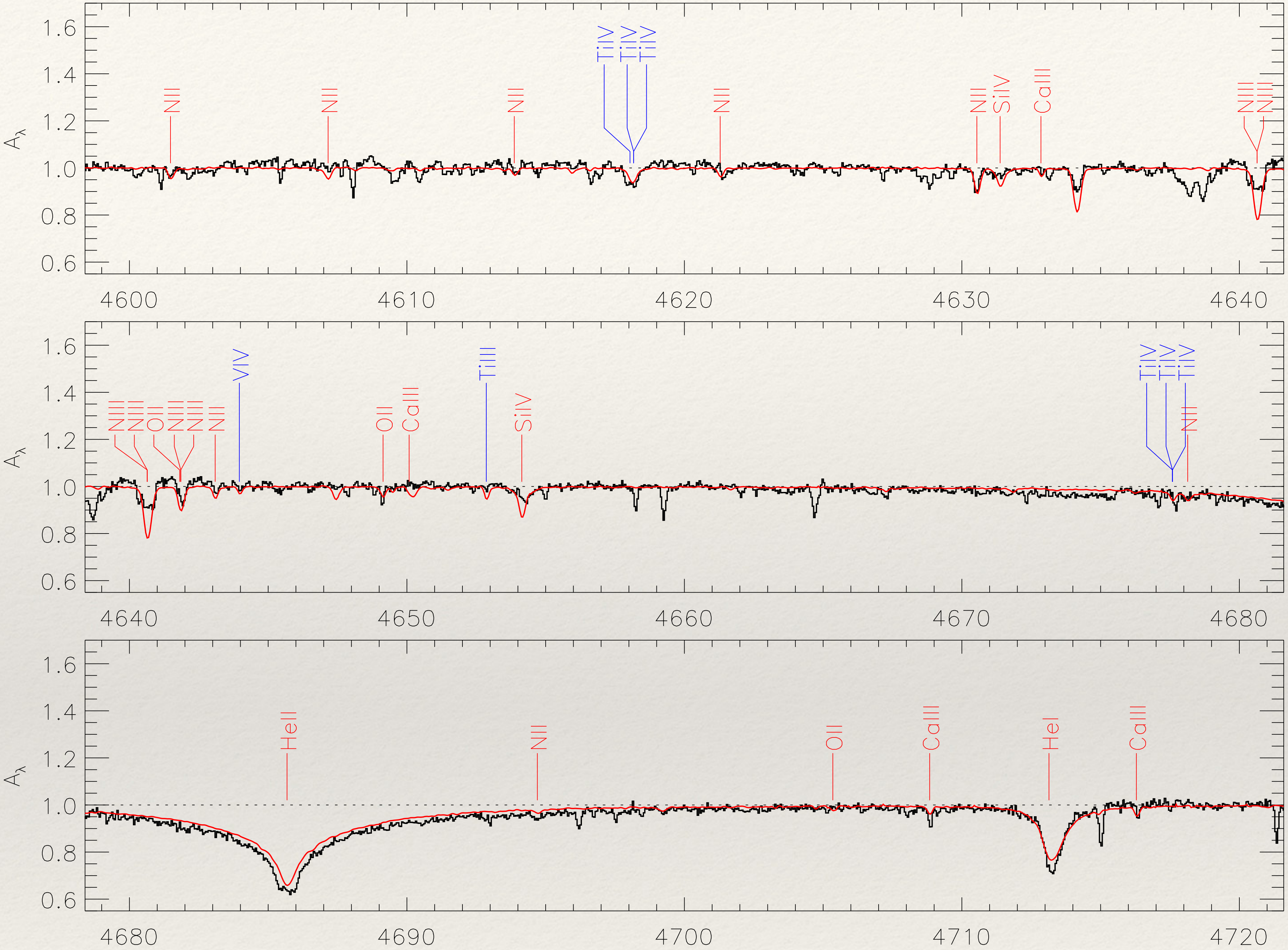
[Fe/H]: metallicity

v_{rad}: radial velocity



.1. Spectral Diagnostics

High-resolution spectrum



T_{eff}: effective temperature

g: surface gravity

n_i: elemental abundances

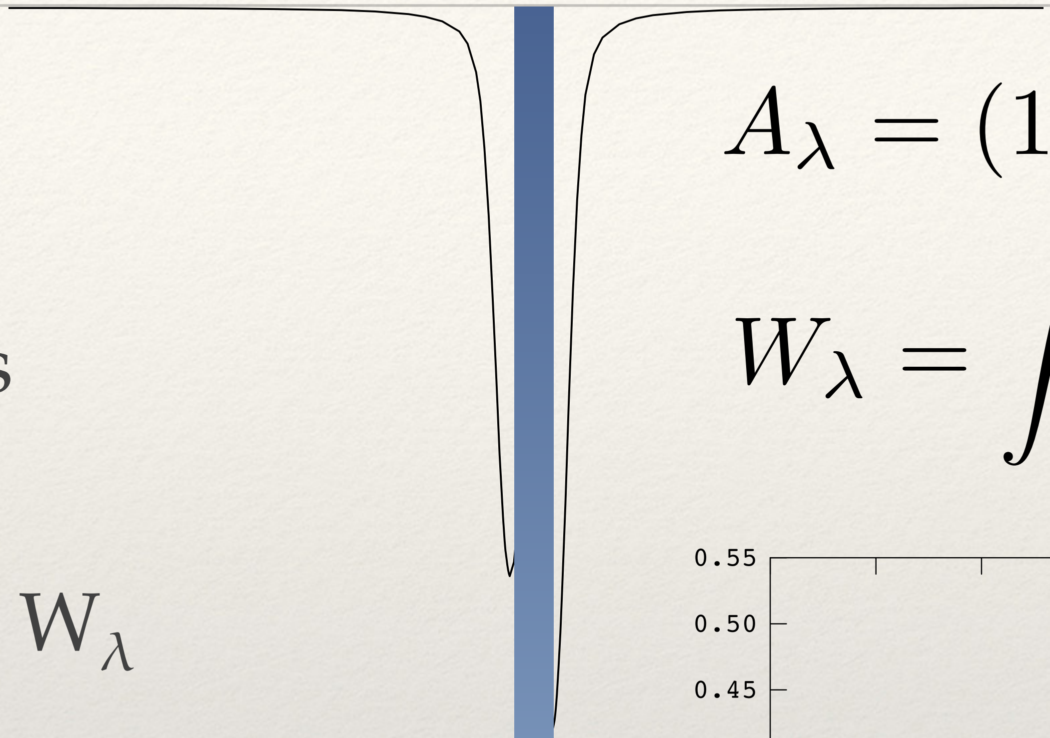
v_{turb}: microturbulent velocity

$v_{\text{rot}} \sin i$: projected rotation velocity

v_{rad}: radial velocity

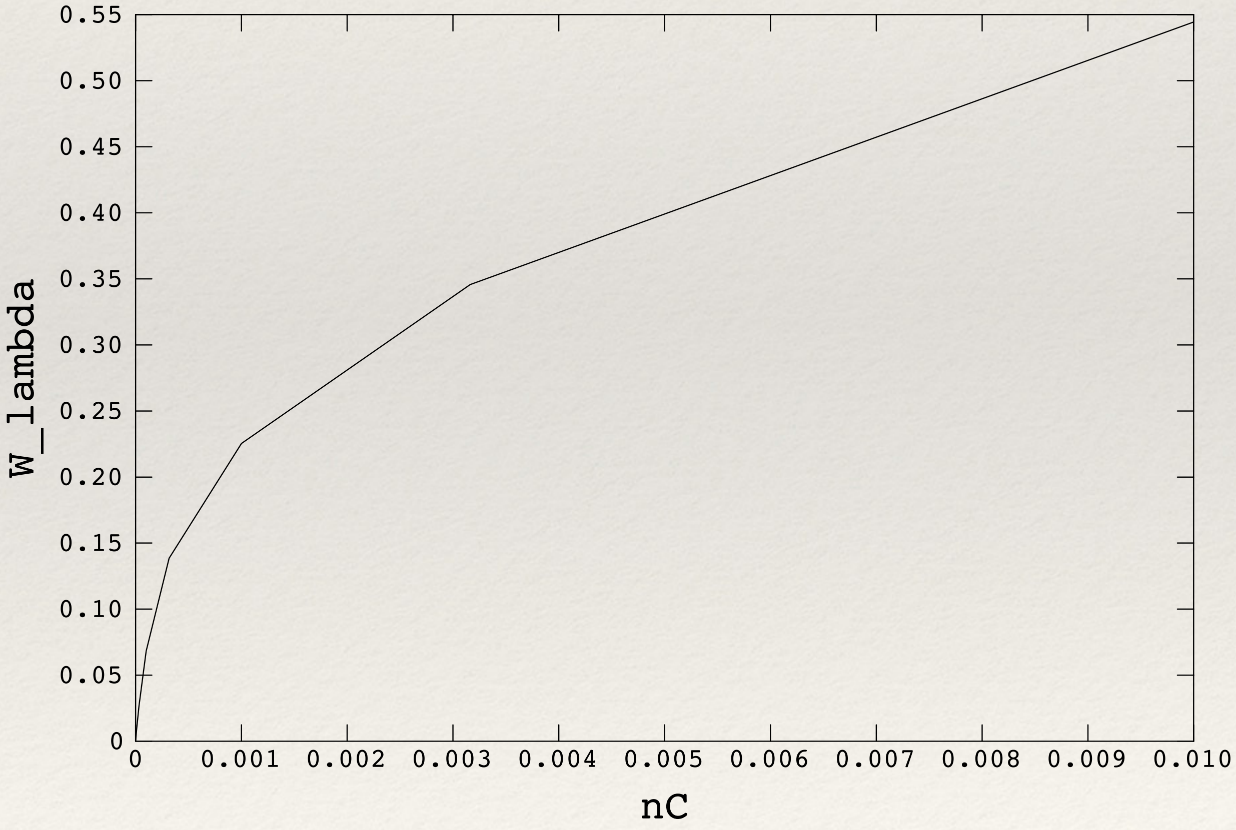
.2. Equivalent widths

- The line profile
- Equivalent widths
- Abundances from W$_\lambda$
- Computing the line profile
- Spectrum synthesis
- Atomic Data



$$A_\lambda = (1 - F_\lambda / F_{\mathrm{continuum}})$$

$$W_\lambda = \int A_\lambda d\lambda$$



.3. The line profile: I

$$A_\nu = (1 - F_\nu / F_c)$$

Pure LTE (no scattering)

$$S_\nu = B_\nu$$

$$F_\nu = \int S_\nu E_2(\tau_\nu) d\tau_\nu$$

$$\tau_\nu = \int_{s_1}^{s_2} \kappa_\nu(s) ds$$

For $F_c : \kappa_\nu = \kappa_c$

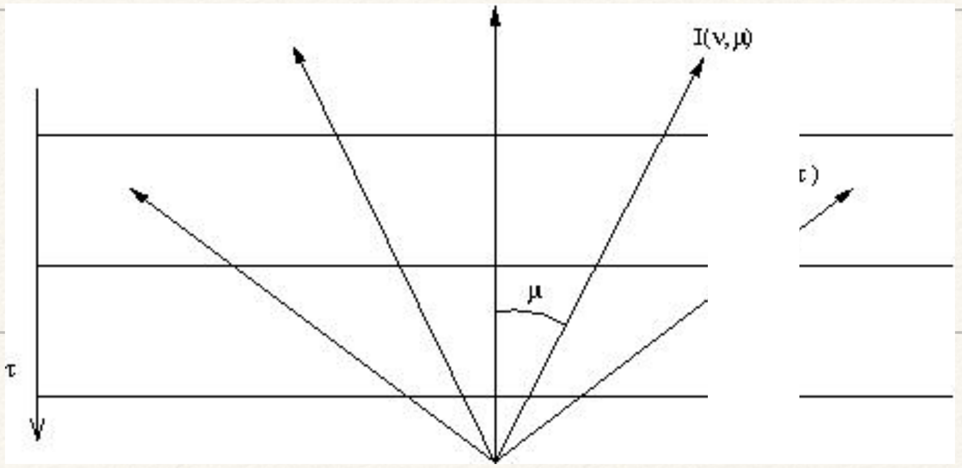
For $F_\nu : \kappa_\nu = \kappa_c + \chi_l \phi_\nu$

Cheap and cheerful !

HOWEVER:

Scattering cannot be ignored at high temperatures and/or low-gravities.

.3. The line profile: II



$$\mu = \cos\theta$$

$$A_\nu = (1 - F_\nu/F_c)$$

$$F_\nu = 2\int_0^1 I_{\nu\mu}\mu d\mu$$

$$I_{\nu\mu} = \int_0^\infty S_{\tau\nu} e^{-\tau/\mu} d\tau$$

$$\tau_\nu = \int_{s_1}^{s_2} \kappa_\nu(s) ds$$

Semi-LTE: including e$^-$ scattering

$$S_\nu = (\kappa_\nu B_\nu + \sigma_\nu J_\nu)/(\kappa_\nu + \sigma_\nu)$$

$$J_\nu = (4\pi)^{-1} \oint I_\nu d\Omega$$

$$S_c : \kappa_\nu = \kappa_c$$

$$S_\nu : \kappa_\nu = \kappa_c + \chi_l \phi_\nu$$

$$\mu \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu$$

MUST solve transfer equation explicitly

.3. The line profile: III

Doppler broadening (thermal, microturbulence):

$$\Delta v_D = \lambda\sqrt{C_T T/A_k + C_v v_t^2}$$

Radiative broadening: Γ_r

Electron (Stark) broadening: Γ_e

Ion (van der Waal's) broadening - heavy ions : Γ_W

⇒Voigt profile:

$$H(a,\nu):$$

$$a = \frac{(\Gamma_\mathrm{r} + n_\mathrm{e}\Gamma_\mathrm{e} + n_\mathrm{H}\Gamma_\mathrm{W})}{4\pi\Delta\nu_\mathrm{D}}$$

$$\nu = \Delta\nu/\Delta\nu_\mathrm{D}$$

⇒line absorption coefficient:

$$\chi_l\phi_\nu = n_{ijk} f_l H(a,v)/\Delta v_D$$

Pressure broadening (quadratic Stark effect) - H, He, resonance lines

.3. The line profile: IV

Temperature: lines from adjacent ions. *e.g.* C^+ *and* C^{++}

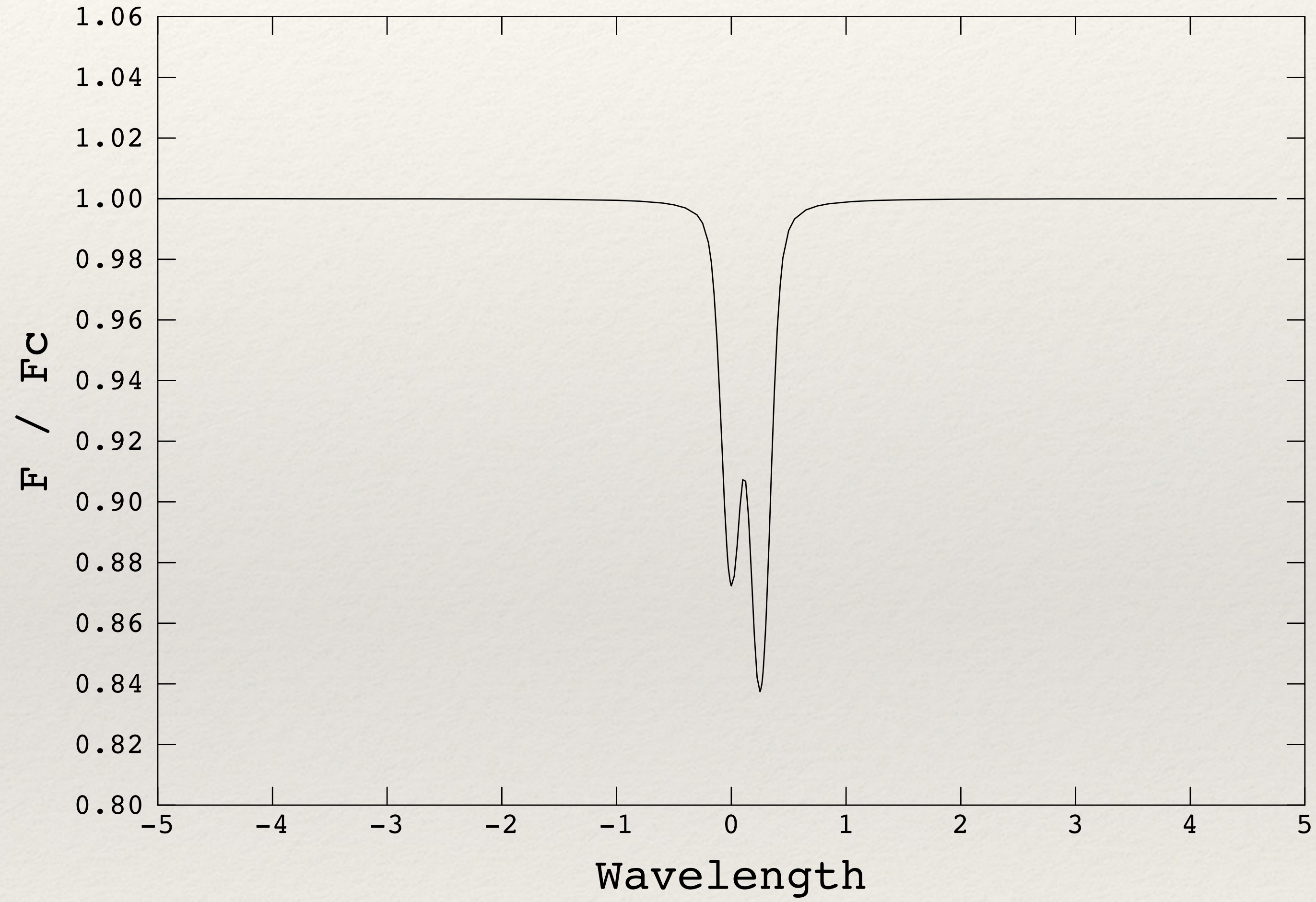
Pressure: lines with strong wings. *e.g. H, He*

Abundance: weak lines

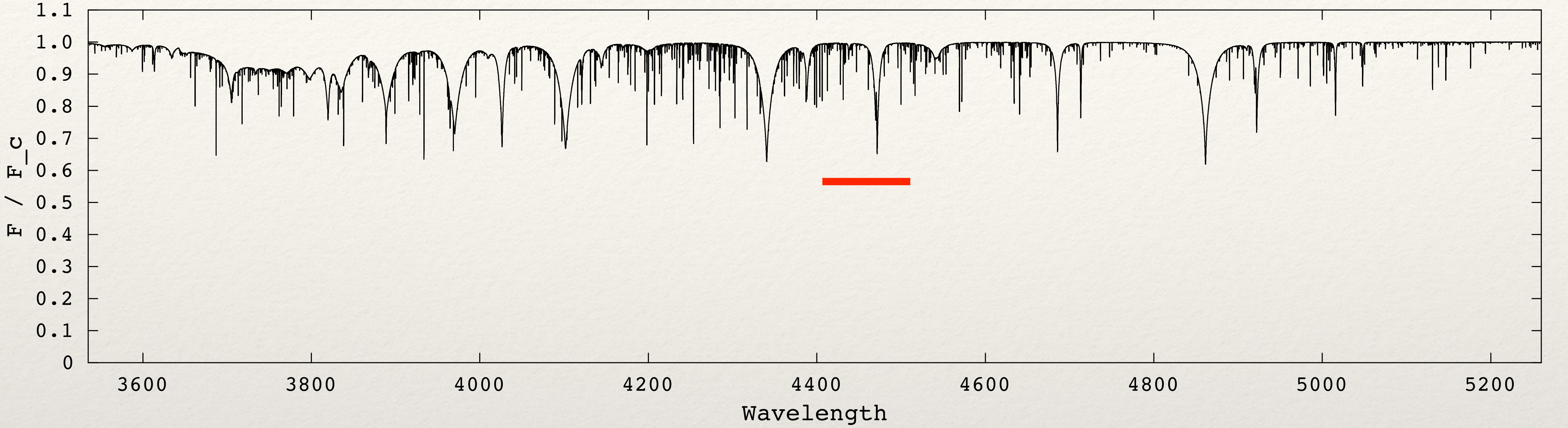
Turbulence: sharp lines. *e.g. from heavy ions:* Fe^{++}

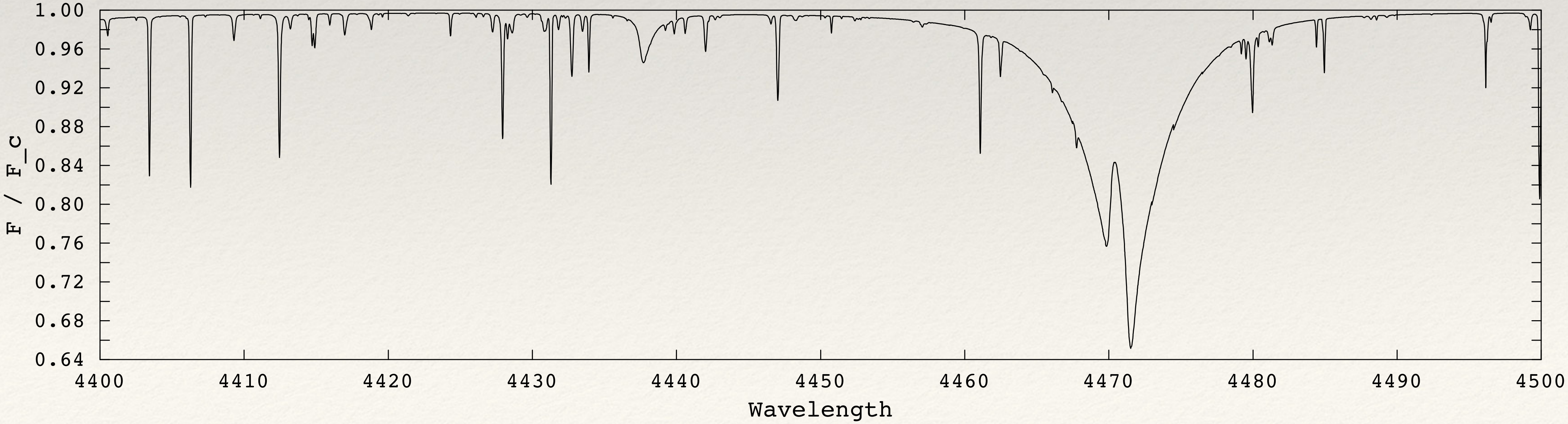
.4. Examples: I - an isolated line

- C II 4267



.4. Examples: II - spectrum synthesis





.5. Atomic Data

For every line:

Z: atomic number
I: ionisation stage
λ: wavelength
gf: transition probability × statistical weight
χ_{ijk}: excitation potential of lower level
Γ_r: radiative damping constant
Γ_e: electron damping constant
Γ_W: ion damping constant

For strong lines:

Pressure broadening coefficients / profiles

H: Vidal, Cooper & Shamey: Lyman, Balmer, Paschen
HeI: Beauchamp et al. (optical), Barnard et al. (4471,4026,4921,4388), Dimitrijevic (various), ….
HeII: Schöning & Butler
Metals: lte_lines

.6. Computational Tools: types

1. Model atmospheres
2. Formal solutions (emergent spectrum, lines, …)
3. Atomic data
4. Interface — theory / observation — analysis
5. Other resources

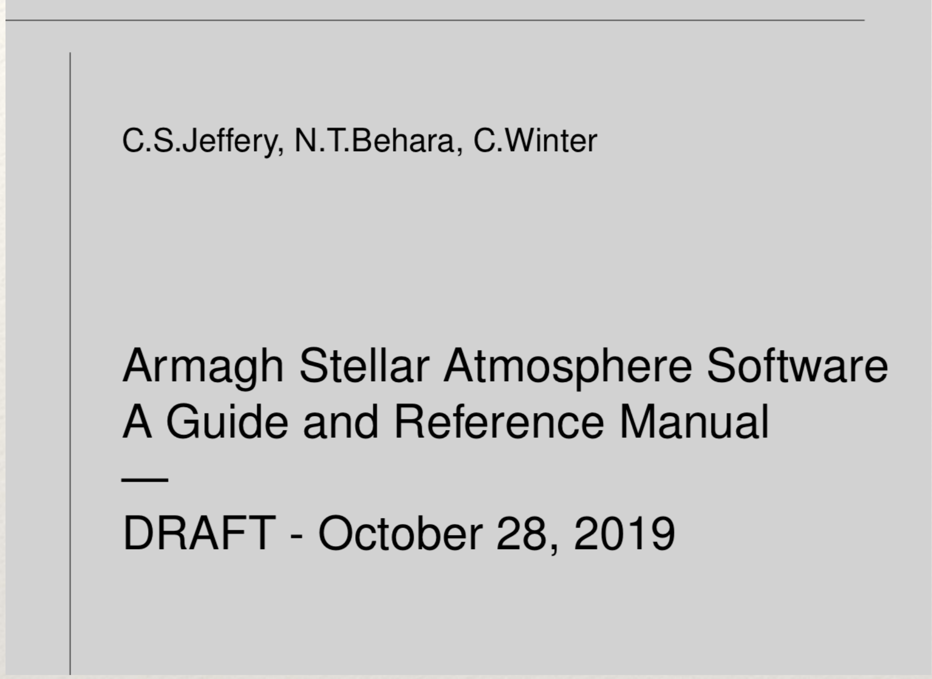
.6. Computational Tools: codes

1. Model atmosphere (structure important, spectrum approximate, photometry)
    1. ATLAS (Kurucz), MARCS (Gustaffson), **STERNE** (**Jeffery+**), …
    2. PHOENIX, TLUSTY (Hubeny), TMAP (Werner)
    3. CMFGEN (Hillier, Crowther), PoWR (Hamann)
2. Formal solution (structure assumed, spectrum crucial)
    1. SYNTHE (Kurucz), **SPECTRUM (Jeffery)**, SPECTRUM (Gray), LINFOR, MOOG (Sneden), SME (Valenti+Piskunov), …
    2. PHOENIX, SYNSPEC, TMAP
3. Atomic data
    1. Kurucz, Tübingen, VALD, NIST, OP, Iron Project, …

lte-codes
Armagh Stellar Atmospheres Software Collection

http://193.63.77.2:2805/~SJeffery/software_store/index.html

- sterne - model atmospheres
- spectrum - formal solutions
- ffit - optimization to fluxes
- sfit - optimization to spectra
- lte_lines - atomic data
- idlines - line identification and fit verification
- [isfit - interactive spectral fitting]



C.S.Jeffery, N.T.Behara, C.Winter

Armagh Stellar Atmosphere Software
A Guide and Reference Manual
—
DRAFT - October 28, 2019

https://armaghop.sharepoint.com/sites/SJeffery/lte_codes/

.7. Spectral Analysis - next time

1. Spectral classification
2. Spectral energy distribution (SED) fitting
3. Coarse analysis (for Teff, log g)
4. Fine analysis (for abundances)
5. Automatic methods (χ^2, ANN, PCA, GA, …)
6. Errors