STERNE:
Model Atmospheres for Hydrogen-Deficient Stars

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1 Description

STERNE[1 2 3 4 5] is a Fortran program for calculating model atmospheres for B- and A-type stars and which especially makes allowances for extreme stellar compositions. It assumes a semi-infinite plane-parallel geometry, local thermodynamic (LTE), radiative and hydrostatic equilibrium. It can allow for a chemically stratified atmosphere, includes additional bound-free opacities due to C and N, and treats the bound-bound absorption using opacity distribution functions. STERNE is an evolving program, as this guide demonstrates. The version described here is version 2.1.

1.1. Structure (STERNE 2.1)

A model atmosphere is defined by the parameters effective temperature ($T_{\rm eff}$), surface gravity (g) and chemical composition.

The optical depth grid (τ_{4000} monochromatic optical depth at 4000Å) presently assumes 50 points on an unequally equally spaced logarithmic scale (unlike that used by Kurucz, for example) (subroutine STAND). Spacing is depth-dependent in order to allow fine spacing in deep layers and coarse spacing in the outermost layers.

The program is started using either a gray temperature stratification or a previously calculated model. The equations of hydrostatic equilibrium are integrated (subroutine HYDRO) using a predictor-corrector method to obtain the gas and electron pressures throughout the atmosphere.

The radiation field, defined by monochromatic fluxes on a pre-defined wavelength grid, is calculated (subroutine FLXODF) using, currently, Avrett and Loeser's method[6] to solve the radiative transfer equation (subroutine AVLO). The maximum number of iterations for the radiative transfer is set to 20 (KIMAX). Iteration will stop if the source function correction is below 10^{-5}. Non-converged wavelengths will be written to output.

The temperature structure is then corrected using the Lucy-Unsöld procedure[7] (subroutine TEMKOR) and the cycle is repeated for a predefined number of iterations or until variations in the total flux throughout the atmosphere become <0.1%. An Ng accelerator[8 9] is currently included to improve convergence. The result is a description of the model structure in terms of optical depth at a given reference wavelength (τ_{4000}), temperature (T), gas pressure ($P_{\rm g}$), electron pressure ($P_{\rm e}$) and opacity (κ_{4000}), and a description of the emergent flux in terms of wavelength (λ) and flux (F_λ).

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1 Wolf R.E.A. 1973: A&A 26, 127
2 Schönberner D., Wolf R.E.A. 1974: A&A 37, 87
3 Heber U., Schönberner D., 1981: A&A 102, 73
4 Heber U., 1983: A&A 118, 39
5 Jeffery C.S., Heber U., 1992: A&A 260, 133
6 Avrett H., Loeser R. 1966: JQSRT 3, 201
7 Lucy 1964: In 'Harvard-Smithsonian Conference on Stellar Atmospheres' p. 93, Proceedings of the First Conference [SAO Special Report No. 167]. Cambridge, Mass.: SAO.
8 Ng K.C. 1974: J.Chem.Phys. 61, 2680
9 Auer L., 1987: In 'Numerical Radiative Transfer' p. 101. ed. W.Kalkofen, CUP.

1.2. Physics

Additional physics included are the equation of state and radiative opacity. The equation of state solves the Saha-Boltzmann ionisation equation for most major species (H, He, C, N, O, ...), including ions up to the 6^{th} ionisation stage. Partition functions are calculated from Chebyshev fits[10] .

Bound-free opacities are mostly taken from Kurucz' code ATLAS6[11] (H I, H^-, He^-, He II, C^-, O I, Mg I, Mg II, Al I, Si I, Si II, Ca II), with the addition of bf opacities for C I-III and N I-III[12] , He I[13] and some later improvements (subroutine KONTOP)

Bound-bound opacities can be optionally excluded to obtain continuum only models. Normally they are treated using Kurucz' ATLAS6 type opacity distribution functions (subroutine LINOP). These are available for H-normal mixtures and for one H-deficient mixture (H=0, He=0.99, C=0.01)[14] .

Scattering coefficients for Rayleigh-scattering (subroutine RAY) and Thomson scattering are also included. The source function contains these scattering terms, i.e. $S_\nu = \rho * B_\nu + (1-\rho) * J_\nu$.

1.3. Problems with the results

1.3.1. Supersonic microturbulent velocity from OII lines

Microturbulence is a phenomenon of unknown physical origin which is required to account for additional line-broadening by the stelar atmosphere which cannot be accounted for by the usual sources (e.g. thermal, radiative, collisional, van der Waal's, pressure). It can be estimated by demanding that the abundance of a given ion species, obtained from several lines covering a large range in equivalent width (W_λ), should be uniform. It has been found[15] that for extreme helium stars with $T_{\rm eff}$~20,000 K, the microturbulent velocity (v_t) determined by the O II lines needs to be at least 20 km/s, somewhat in excess of the local sound speed. Possible explanations involve incorrect temperature stratification in the model atmosphere or the inappropriate use of LS coupling to determine branching ratios for line oscillator strengths[16] .

1.3.2. Conflict between flux distribution and HeI lines for A-type H-def stars

Flux distributions for H-deficient binaries give $T_{\rm eff}$~12,000 K, whereas He I line profiles require $T_{\rm eff}$~14,000 K, implying that the theoretical lines are not being formed at the correct optical depth, (i.e. incorrect temperature stratification)[17] . The rôle of UV-line opacity in the structure of the model atmosphere at these temperatures is very severe.

1.3.3. Convergence at low optical depths

It has proved difficult to achieve convergence of the temperature correction in low-g H-def atmospheres at the accuracy normally desired. This appears to be related to the fact that the existing radiative transfer solution leads to a nett rise in the source function (S_ν) and temperature at very low optical depths, which should be physically impossible in LTE. The Avrett-Loeser method may not be stable over very large ranges in optical depth (STERNE treats log τ = -7...2, whilst ATLAS treats log τ = -4...2).

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[10] Traving G., Baschek B., Holweger H., 1966: Abhandlungen der Hamburger Sternwarte VIII, 3
[11] Kurucz R.L., 1970: ATLAS: A Computer Program for calculating Model Stellar Atmospheres, SAO Special Report No. 362, Cambridge, MA 02138
[12] Peach G., 1970: Mem.R.astr.Soc. 73, 1
[13] Koester D., et al. 1985:
[14] Möller R., 1990: Diploma Thesis, Universität Kiel.
[15] Jeffery C.S. & Heber U. 1992: A&A 260, 133
[16] Liu X.-W., Storey P.J., Barlow M.J., Clegg R.E.S. 1994: MNRAS
[17] Dudley & Jeffery 1993: MNRAS 262, 945.

2 Structure of the program (STERNE 2.1)

2.1. Documentation and Libraries

STERNE has been decomposed from its original monolithic structure into a number of subroutine libraries, partly in an attempt to integrate some STERNE utilities with other CCP7 programs, including SPECTRUM and TAP. At present this process is not complete, and the STERNE libraries are practically self-contained units. The libraries currently required by STERNE.2.1 are:

stn	main program, radiative transfer and temperature correction subroutines
opk	Kiel bf and bb opacities, including peach tables
tap	Theoretical Astrophysics: a CCP7 library of theoretical applications
chr	Starlink character and string handling subroutines

2.2. Subroutine structure (library stn.2.1)

STERNE: Main program

(a)Data initialisation

Read start parameters and/or initial model
INDAT: Read wavelength data
BAND: Read wavelength data
STAND: Define some standard values
STRATI: Setup the H/He stratification
PEACH: Read in continuous opacity data

(b)Temperature correction loop

ATFILL: T-dependent opacity data to common blocks
HYDRO: Integrate hydrostatic equilibrium

> PRESS: Equation of state
> ION (opk): Calculate ionisation ratios for a given species
> OPK_RBF: Continuous radiative opacity
> OPKC(opk) : Continuous opacity
> INGRAT: Integrates over optical depth

IONFRN (opk): Caclulate ionisation data and copy to opacity common blocks
FLXODF: Radiative transfer to calculate emergent flux

> KONTOP: Calculates total continuous opacity
> OPK_RBF: Continuous radiative opacity
> OPKC(opk) : Continuous opacity

LINOP: Calculate total line opacity
TAUNUE: Calculate optical depth scale at current frequency

> INGRAT: Integrates over optical depth
> AVLO: Solve radiative transfer equations using Avrett-Loeser method
>
> > BNUE: Evaluate Planck function B_ν
> > GH: Coefficients for matrices
> > ALKOEF: Solution of matrix equations
> > INTP: Interpolate final solution of emergent flux
> > FEHLER: Test for convergence of solution

TEMKOR: Temperature correction
OUTSTAT: Report convergence statistics for this iteration
OUT1: Print a summary of the current model

(c)Output final model

OUT1: Print statistics for final model
Write current/final model to file

2.3. Construction of the executable image

The main components of the model atmosphere program are located in the folder *$(CCP7)/sterne/sterne.2.1*. The elements are contained in a text/object library triplet: *$(CCP7)/sterne/sterne.2.1/sterne.2.1.a* (text library), *$(CCP7)/bin/libstn.a* (random object library) and *$(CCP7)/bin/libstn.so.2.1* (shareable object library). These may be linked, using *$(CCP7)/sterne/sterne.2.1/makefile*, with the command

    make libstn.a

Care must be taken when linking with libary opk because certain common-blocks are shared, and if changes are made thay must be propagated through all object binaries. The executable image is constructed using the same *makefile* with the command

    make sterne

To install sterne in *$(CCP7)/bin*, then

    make install

2.4. Running the program

STERNE 2.1 may be run simply using the script $*(CCP7)/sterne/Sterne*, which takes the following arguments:

Sterne *datafile odf [interval [model]]*

Sterne is available as a command if the CCP7 environment is enabled, i.e. if properly installed there is a symbolic link in $(CCP7)/bin/Sterne.

datafile contains all the parameters describing the model to be calculated. It is described fully in section 3. In normal use it can be created BEFORE running Sterne as above with the utility

Sterne.input T_{eff} *log_g* n_H n_{He} n_C n_N *grey datafile*

where the various data are as follows:

T_{eff}	Effective temperature (K)
log_g	logarithm of surface gravity (cgs units)
n_H n_{He} n_C n_N	Fractional abundances by number of hydrogen, helium, carbon and nitrogen
grey	Flag indicating starting model, 0 = grey, 1 = previous model
datafile	Name of file into which to store parameters

More advanced use of STERNE requires careful manipulation of *datafile*, for example if abundances of other species are to be altered from their solar values or a stratified composition is required.

odf is the name of the file containing the opacity distribution. Currently allowed values are dfbhe90 and dflhe90, corresponding to opacity distribution functions for He-rich mixtures.

If a previous *model* is being used, either to start a new calculation or to determine the final flux distribution from a previous calculation, then interval should specify the size of the wavelength interval in the opacity distribution as BIG or LIT.

In the case that a final flux distribution is to be calculated using a ‘little interval’ odf, *datafile* can take a very simple form, consisting primarily of dummy values. In this case the command to calculate the model can be simplified to

Sterne.final *odf model*

where *odf* and *model* maintain their earlier meaning.

Output goes to the following files (see section 4).

datafile.output	Progress of calculation (stdout)
datafile.2	scratch
datafile.3	current model
datafile.MODEL	final model

2.5. Program folder structure

flux	grids of model fluxes
grid	grids of model structures
qub	grids of model structures in qub format
odfs	opacity distribution functions and related files
peach	peach opacity tables (now use those in $(CCP7)/spectrum/data)
utils	some format conversion programs
sterne.2.1	source and makefiles for STERNE 2.1
opk	opacity library (used by STERNE 2.1)
sterne.3	source and makefile for STERNE 3
stn	main library (to be used by STERNE 3)

3 Data Files (STERNE 2.1)

The following data files have to be supplied:

datafile: parameter file which specifies model atmosphere parameters (Teff, log g, abundances) and action parameters. Usually read from Standardinput by a Here-document.

peach: opacity tables for continuous opacities of C and N (Peach-tables **-** binary format file fort.3).

wave: file containing wavelength grid and line list including atomic data for calculating explicit line opacities if required. To calculate continuous opacity models or ODF-models a dummy (H-) line has to be inserted. Two sets of wavelengths have to be specified. One for continuum wavelengths and a set for continuum plus line wavelengths. In order to run continuum or ODF models, these sets have to be identical. Formatted file: WAVE, example file WAVEKUR for calculating ODF-model with "big" ODF intervals. Note that the wavelength mesh has to be consistent with the ODF-tables used.

odf: ODF tables for line opacities if required. Binary format fort.10.

model: previously calculated model atmosphere to do further iterations on the same model or to scale it in order to calculate model for near-by parameters. Formated file MODIN.

Files odf and model are optional. Files peach and wave are supplied.

3.1.Structure of datafile

(free format)

Line 1	Teff, log g, x_C, x_N, x_i (i=1,7)
Line 2	n_i/n (i=1,7)
Line 3	lm, nzs, ifi, ipu, ibl, ifl, kimax
Line 4	isw1, isw2, ios, intst, ebmv, iel, taux0, alphax(iel,1)
Line 5	opakey
Line 6	wlmin wlmax: min and max wavelengths

3.1.1. Explanation of parameters

Line 1

Teff	Effective temperature (K)
log g	logarithm of surface gravity (cgs)
x_C	carbon abundance: log $n_C/n_{C_\odot}$
x_N	nitrogen abundance: log $n_N/n_{N_\odot}$
x_i	abundance of species i: log $n_i/n_{i_\odot}$, i=1,7 => O,Mg,Al,Si,S,Ca,Fe

Line 2

n_i	fractional abundance by numbers: n_i/n: i=1,7 => H,He,Li,Be,B,C,N The abundances for C and N supercede values specified on line 1, unless n_i=0.

Line 3

lm	First iteration =1 => grey or converged model as starting approximation >1 => read a partially converged model for further iteration
nzs	Last iteration
ifi	H opacity flag 0 => hydrogen line opacity included 1 => hydrogen line opacity NOT included
ifo	Iteration at which full print-out is to be made if not converged
ipu	0 => write final model to a binary file 1 => do not write to binary file
ibl	
ifl	
kimax	maximum number of iterations in radiative transfer solution (AVLO).

Line 4

isw1	Start model 0 => Read partially converged model 1 => DO NOT read partially converged model
isw2	Start model 0 => Gray atmosphere 1 => Read previously convergeed model
ios	
intst	
ebmv	Extinction E(B-V) for calculating reddened fluxes (redundant)
iel	Element defining chemical stratification in atmosphere
taux0	Optical depth above/below (?) which atmosphere is homogeneous
alphax (iel,1)	Abundance of element iel at top of atmosphere

Line 5

opakey	'CONTINUUM' or 'ODF' selects whether an opacity distribution provides line opacity

Line 6

wlmin	minimum wavelength included in flux calculations
wlmax	maximum wavelength included

3.1.2.

3.1.2. A summary of choices:

a. From grey model => new model
b. From partially converged model, same parameters => new model
c. From fully converged model, different parameters => new model
d. From fully converged model, same parameters => final flux distribution

3.2. Abundances

Abundances are specified in two ways: Chemical elements H and He have to be specified explicitly (number fractions) in *datafile*. C and N can either be specified explicitly (number fractions) or relative to solar abundance (log of scaling factor). Other element abundances are specified relative to solar values (log of scaling factor). Solar abundances are from Holweger (1979). Since the program is supposed to run at various H/He ratios a built-in scaling is done to preserve the usual normalisation (log(sum of mass fraction) equals 12.15) (subroutine INALPHA). The sum of the number fractions specified has to be 1.00 ± 0.01 (renormalised later on) otherwise program execution is stopped in order to avoid calculations for obviously mis-typed parameters.

3.3. Calculation of emergent flux (no temperature correction)

The emergent flux on a finer wavelength mesh (e.g. WAVEKURL for the "little" ODF-intervals of Kurucz) can be calculated from a converged model atmosphere by reading that model and setting the number of iterations to zero. The wavelength mesh has to be consistent with the ODF-tables used. The resulting fluxes are written to the model file and can be used for evaluating colours with an additional program (Heber, Schönberner, 1981), or reddened using DIPSO.

3.4. Stratified model atmospheres

The atmosphere need not be homogeneous. A depth-dependent H/He abundance ratio can be created by specifying a transition optical depth and ratios at depth and outer boundary (subroutine STRATI). The transition is smooth by using a Gaussian profile for the depth variation of the abundances.

4 Output files

The following files are created by STERNE:

datafile.output (*stdout*): Standard output contains information on the convergence of the source function for every iteration. Details of the model are recorded at every 5th depth point for every 3rd iteration. These show the temperature correction and the difference between the integrated flux and expected flux at each depth zone, as well as optical depth, temperature, gas and electron pressures, opacities, etc. The final model is printed completely, including ionisation equilibria for H, He, C and N, and the final emergent flux distribution.

datafile.MODEL: The final model is printed out in concise form, starting with $T_{\rm eff}$, log g, and composition. The temperature, gas and electron pressures, optical depth and opacity are printed for each depth zone. Any composition stratification is defined, and the flux distribution is recorded.

datafile.2: A scratch file used for temproary storage of radiative transfer matrrices

datafile.3: The current model in binary format

5 Model Atmosphere Grid (STERNE 2.1)

5.1. The grid of calculated models

Model atmospheres have been constructed on limited temperature and gravity grids for a number of compositions, mostly hydrogen-deficient. Each grid is now given a label corresponding to the composition of H, He, C and (optionally) N. Earlier grids were given an arbitrary label.

Label ttgg+	n_H	n_{He}	n_C	n_N	[Z]	T_{min}–T_{max} (kK)	Opacity	Study
0099010	.0	.990	.010	.003	0.0	22 – 28	dfbhe90	LSS 3184
0099005	.0	.990	.005	.006	0.0	20 – 28	dfbhe90	LSS 3184
old models								
c03	.000	.996	.0030	.00025	0.0		continuum	
c06	.000	.992	.0060	.00025	0.0		continuum	
c10	.000	.989	.0100	.00025	0.0		continuum	
he99	.001	.996	.0014	.00030	0.0		continuum	
n02	.0016	.995	.0001	.00202	0.0		dfbhe90	υ Sgr
b00	.001	.996	.0014	.0003	0.0		dfbhe90	BD–9 4395
b10	.001	.987	.0100	.0005	0.0		dfbhe90	BD–9 4395
h10	.100	.889	.0100	.00028	0.0		dfbhe90	DY Cen
hd144941	.100	.898	.0010	.0002	0.0		dfbhe90	HD144941

Within each grid, models are calculated as close to the Eddington limit as possible, starting from a surface gravity log g ~ log g_{Edd} +2.0. Each model is now labelled:

ttgghhheccc[nnn][L]

where tt = T_{eff} * 1000, gg = log g * 10, hh = n_H * 100, he = n_{He} * 100, ccc = n_C * 1000, nnn = n_N * 1000. L denotes that models have been computed using ‘little’ interval odfs.

5.2. Formats and conversion utilities

The model atmospheres are available in three formats.

(a) STERNE output: /simon/sterne/grid/....MODEL

This format can be reread by STERNE in order to start or restart a model calculation (models calculated on the RAL Cray have not yet been transferred to the Sun from the VAX). A conversion utility *'sterne_format'* found in the directory *$(CCP7)/sterne/utils* translates these files into the following 2 formats.

(b) DIPSO fluxes: /simon/sterne/flux/....f

This format can be read by DIPSO for comparison with observed flux distributions. Until recently most of the blanketed models were calculated with 'big' interval odfs..
Two formats have been used.
i) a 'free format' with no header information: the first line contains the number of wavelengths, subsequent lines contain one wavelength and flux per line. Multiply the fluxes by π to obtain astrophysical fluxes.
ii) recent files contain two additional header lines at the beginning, defining the T_{eff}, log g, and composition of the model and the date and time of computation.

(c) SPECTRUM input: /simon/sterne/qub/....q

This format can be read by the QUB spectrum synthesis program.

6 Future Developments (STERNE 3 and beyond)

6.1. General

The program requires a major overhaul in terms of removing dead pieces of code, improving code structure with modern Fortran and properly-designed subroutine and common-block libraries, revision of the i/o handling, especially the specification of the starting model and various switches. Some of these are in progress for STERNE 3. Documentation, including references for all of the physics (eg opacities) needs to be written.

6.2. Hydrostatic Equilibrium

The existing predictor-corrector integration requires a Runge-Kutta integration to start it off. There is no strong reason for preferring PC over RK methods[18] , and the combination of two methods makes the code unnecessarily complex. The RK integration will be extended over the whole atmosphere.

The exisiting models use a monochromatic optical depth scale. Since this is not easily comparable with other calculations (it depends on the opacity!), it should be replaced by a mass scale. The code should also be able to allow different zoning to be defined at input for experimental purposes.

6.3. Radiative Transfer and Temperature Correction

(a) Feautrier scheme

The Avrett-Loeser scheme, which is an iterative method, does not converge very well, particularly in the outer layers of hydrogen-deficient low-gravity atmospheres, where the opacity is very low. The radiative transfer solution needs to be replaced by a linear scheme, such as a Feautrier scheme[19 20] . I have written a subroutine for executing the Feautrier scheme which is well-tested within the spectrum synthesis code SPECTRUM, and should be easily ported to STERNE. I have been coding some of this over the last 12 months, preparing for STERNE 3. This work is being continued by a research student at St Andrews, Paul Harrison.

(b) Steiner's method

The bottle neck in STERNE 2.1 is the slow convergence of the Lucy-Unsöld temperature correction procedure. A massive acceleration in overall execution can be achieved by adopting an operator perturbation technique[21] for the temperature correction procedure. This can be impemented in a straightforward way by replacing the existing subroutine TEMKOR.

(c) Rybicki scheme + Complete Linearization

The current iterative procedure (hydrostatic equilibrium > radiative transfer > temperature correction) can be replaced by a complete linearisation of all equations into a single set of simultaneous equations[22] . This is an extension of the Feautrier system, and could be implemented but at lower prioirity than using Steiner's method.

6.4. Opacity Distribution Functions: bb opacity

Tests with the ATLAS6 odfs showed that, probably, the models are still missing substantial amounts of UV opacity. ATLAS6 odfs were constructed from a linelist of about 750,000 lines[23] . Subsequently

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[18] Press W.H., Flannery B.P., Teukolsky A.A., Vetterling W.T., 1989: 'Numerical Recipes' p.569, Cambridge University Press

[19] Feautrier P. 1964: C.R.Acad.Sci.Paris 258, 3189 & Mihalas D.

[20] Mihalas D. 1978: Stellar Atmospheres 2nd ed. p.156, Freeman, New York

[21] Steiner O., 1990: A&A 231, 278

[22] Mihalas D. 1978: Stellar Atmospheres 2nd ed. p.180, Freeman, New York

[23] Kurucz R.L. & Peytremann E., 1975: A Table of Semiempirical gf Values, SAO Special Report No. 362, Cambridge MA 02138.

Kurucz computed new odfs for ATLAS9 using data for 10^7 lines[24] and showed substantial imrovements for H-normal model atmospheres. No odfs were calculated for H-deficient models. We need to:

(a) calculate new odfs

calculate new ATLAS9-type odfs for H-deficient models (we need to be able to do this for a range of compositions). Colleagues in Vienna have offered to collaborate on calculating these.

(b) modify STERNE

modify STERNE to accommodate the new odfs, which have higher frequency sampling than the ATLAS6 odfs. Again, much of the coding for these modifications has been prepared for STERNE 3.

6.5. Continuous opacities: bf opacity

The Opacity Project has calculated a large number of bound-free opacities (photoionisation cross-sections). At the very least these need to be compared with the existing bound-free opacities used in STERNE. Better, the OP cross-sections should replace the Kurucz cross-sections, including some authentic treatment of the PEC resonances. This work needs to be carried out in collaboration with Dreizler and Heber (Bamberg), Werner (Kiel), Barstow (Leicester), and, possibly, Butler (Munich).

6.6. Monochromatic opacities and equation of state: bf+bb opacity

In addition, the OP has calculated tables of monochromatic absorption coefficient (κ_λ) for all atomic species considered by the project[25]. These are tabulated, along with equation of state data for a wide range of temperature and (reduced) density. In principal, using an appropriate sampling technique (Gelaitis ?), these data could be used to replace ALL of the EoS and opacity data currently used in the code, providing access to not only, for example, improved partition functions and atomic data, but also to physics completely independent physics from that used in any other model atmosphere code. One drawback, is that the lowest densities tabulated by OP are not low enough for the model atmosphere project.

6.7. Convection

The rôle of convection in H-deficient stellar atmospheres has been claimed to be significant at higher effective temperatures than in H-normal atmospheres[26]. This is puzzling because, in general, the total opacity is considerably lower. Much depends on the nett contribution of He I opacity when the He I ionisation zone occurs in the stellar atmosphere. The effective temperature at which convection starts to become significant needs to be verified.

[24] Kurucz R.L. 1991: In ‘Stellar Atmospheres: Beyond Classical Models’, NATO ASI Series C-341, p. 441. eds. L.Crivellari, I.Hubeny & D.G.Hummer, Kluwer, Dordrecht
[25] Seaton M.J., Yan Y., Mihalas D., Pradhan A.K., 1994: MNRAS 266, 805
[26] reference misplaced