A new "hybrid" grid for STARS97

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1 Introduction

While awaiting the arrival of the Pauldrach 25kK main sequence (MS) and Super Giant (SG) models, I have created some IDL modules that enable me to interpolate between any set of "corner stone" SEDs. In addition I have written tools to examine the smoothness of the resulting grid.
Using these routines I have constructed a new *hybrid* grid, consisting of the *Pauldrach* grid (T_{eff} $\geq$25kK), the *Pauldrach-Kurucz transition* grid (19<T_{eff} <25) and the *cold Kurucz* grid (T_{eff} $\leq$19kK).
This document has been written to document the steps I took to derive the new hybrid grid. Hopefully, it will also evoke critical remarks as to the methods I used.

2 The interpolated Pauldrach grid

The method used to establish the interpolated Pauldrach grid is very close to the method described by Tal Alexander (private communication).
First, a common wavelength grid is compiled from all available Pauldrach models (module CREATE_PAUL_BASE). Then the 12 "corner stone" models (6 MS models and 6 SG models, at T_{eff} 25,30,35,40,45 and 50kK) are converted from flux density distributions into $T_{rad}(\lambda)/T_{eff}$ ("T-ratio") distributions (module FLUX_TO_T_RATIO). Each of these T-ratio distributions is then interpolated to the Pauldrach common wavelength grid (module REBIN_T_RATIO). It is on this level that the corner stone models can be interpolated and extrapolated to a denser grid.
The most important step in the construction of the grid is the interpolation between the six MS models and the interpolation between the six SG models. In both cases module POLATE_TEFF is used (see subsection POLATE_TEFF within section "Description of the IDL modules" for the interpolation formula). In the latter case the corner models not only differ in T_{eff}, but also in log(g). Since the differences between two adjacent SG corner models is only 0.2—0.25 in log(g), the SG interpolation result is quite acceptable.
Using the MS and SG branches as grid "backbones", the models in between can be computed using module POLATE_GLOG (see subsection POLATE_GLOG within section "Description of the IDL modules" for the interpolation formula). Note that the T-ratios for interpolated models are only non-zero at those wavelengths at which *both* corner SEDs are defined.
All interpolated models are now converted from T-ratio distributions into flux density distributions (module T_RATIO_TO_FLUX). Flux conservation is ensured (module FLUXFRAC) through the application of a flux correction factor.
The Pauldrach grid extends over a T_{eff} range of 25–52kK (in steps of 1kK) and from log(g)=4.0 down to log(g)=2.75 for T_{eff}=25–27kK, down to log(g)=3.0 for T_{eff}=28-32kK, down to log(g)=3.2 for T_{eff}=33–37kK, down to log(g)=3.4 for T_{eff}=38-42kK, down to log(g)=3.6 for T_{eff}=43-47kK, and down to log(g)=3.8 for T_{eff}=48–52kK (in steps of 0.2 above log(g)=3.0 and in steps of 0.25 below log(g)=3.0).

3 The Pauldrach–Kurucz transition grid

Corner stone models for this grid are the Kurucz MS model at T_{eff}=19kK & log(g)=4.0, the Kurucz SG model at T_{eff}=19kK & log(g)=2.5, the Pauldrach MS model at T_{eff}=25kK & log(g)=4.0 and the Pauldrach SG model at T_{eff}=25kK & log(g)=2.75.
Again, first the two "backbones" are computed — the MS and SG models at T_{eff} 20, 21, 22, 23 and 24kK. Then, for each of the above T_{eff} values the MS and SG models are interpolated from log(g)=4.0 down to log(g)=2.5 for T_{eff}=20–22kK and down to log(g)=2.75 for T_{eff}=23–24kK.

4 The cold Kurucz grid

The low temperature part of the hybrid grid (T_{eff} ≤19kK) is populated by Kurucz models. The log(g) values of this *cold Kurucz* grid are 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 2.75, 3.0, 3.2, 3.4, 3.6, 3.8 and 4.0. Since the original Kurucz grid has no models at log(g) values of 2.75, 3.2, 3.4, 3.6 and 3.8, we copied the Kurucz models for log(g)=3.0 over to log(g)=2.75 and log(g)=3.2; the Kurucz model for log(g)=3.5 to log(g)=3.4 and log(g)=3.6 and the Kurucz model for log(g)=4.0 to log(g)=3.8.

5 What has changed in the grid?

The log(g)=4.5 and log(g)=5.0 Kurucz models which were used in the previous hybrid grid to complete the high temperature part are now out. Instead, within the range T_{eff}=20–50kK the log(g)=4.5 and 5.0 grid points are populated with the log(g)=4.0 model of the same T_{eff}.
With the availability of a log(g)=2.75 Pauldrach model at T_{eff}=25kK, the lower log(g) boundary between 20 and 30kK is pushed to lower log(g) values. By adding log(g)=2.75 to the set of grid log(g) values, the jumps in the low log(g) boundary are now smaller as well.
Furthermore, extrapolated Pauldrach models have been computed for T_{eff}=51–52kK and log(g)=3.8–4.0. The corresponding log(g)=4.5 and 5.0 points are populated with the log(g)=4.0 model of the same T_{eff}. In addition, the next higher temperature in *spec_grid.dat* has been changed from 52kK to 54kK. All of this should lead to an extension of the nearest neighbour search to higher temperatures than before.

6 Differences between "lin" and "log" grid

The IDL modules POLATE_TEFF and POLATE_GLOG can interpolate between corner models in two ways: "linearly", using T-ratio in the interpolation, or "logarithmically", using log(T-ratio) in the interpolation (see Sections 8.5 & 8.6 below for the formulae). Hence, I computed two versions of the hybrid grid: a "lin" and a "log" grid.
Using the IDL modules INTEGRATE_HYBRID and SHOW_INTEGRATE I was able to compute and visualize differences in the integrated fluxes of all grid models. Both grids appear to be smooth within most of the assessed frequency bins (e.g. 1.10–1.15 Ryd, 1.20–1.25 Ryd, 1.30–1.35 Ryd, etc.). Only at higher energies (>3 Ryd), the breaks between the *Pauldrach* grid, the *Pauldrach-Kurucz transition* grid and the *cold Kurucz* grid start to become discernable.
I also compared the results obtained for the *linear* and *logarithmic* grid. Within the *Pauldrach* grid the differences between the *linear* and *logarithmic* grid are less than 10% below 3 Rydberg, and can be as large as 40% above it. The situation is worse for the *Pauldrach-Kurucz transition* grid: differences can be a factor of 2!
The reason for considering a logarithmic grid in the first place was the interpolation of T-ratio SEDs at long wavelenghts (>100μm). At these wavelengths the T-ratios are very high and very different for a MS and a

SG corner stone model of the same T_{eff}. Linear interpolation in that range gives *very* different results from the logarithmic interpolation.
I also found that extrapolation to 51–52kK results in *negative* fluxes (λ >100μm) when this is done linearly. When done logarithmically, negative fluxes cannot occur. Attempts to extrapolate to log(g)=4.2 and log(g)=4.5 were abandoned for the same reason. Whether the *extrapolated* SEDs are *astrophysically* feasible is an entirely different question. Dietmar Kunze inspected some of the log(g)=4.5 results and noticed that some ionization edges had gone into emission, something that is astrophysically impossible according to him.

7 What has changed in the STARS spectra?

STARS spectra, computed using the old hybrid grid, were compared with the new linear hybrid grid for the following parameters: α=2.35, $\tau=10^6$yrs, M=[0.8,120] $M_{\odot}$, track mass-loss "low" and track type "t020" (641 masses; AGB phase completed with thermal pulse phase).
In contrast to the Kurucz atmospheres, the Pauldrach atmospheres are nearly featureless at energies below 0.9 Ryd. The replacement of the log(g)=4.5 and log(g)=5.0 Kurucz SEDs by Pauldrach log(g)=4.0 SEDs at temperatures above 19kK can therefore be easily verified by looking for the presence of features in the STARS SED of a young ($t<2\cdot10^7$yr) cluster.
The other mayor change between the old and the new hybrid grid is the replacement of the *Kurucz* T_{eff}=25–30kK grid by the 25–30kK *Pauldrach* grid and the replacement of the *Kurucz* T_{eff}=20–24kK grid by the *Pauldrach-Kurucz transition* grid. Since none of the Pauldrach SEDs has a jump at 1.8 Rydberg, and the Kurucz SEDs do, the difference between the old and the new hybrid grid should be clearly visible around 1.8 Rydberg. Indeed, at ages in excess of $15\cdot10^6$yr, the two grids show distinct differences at this He-I edge. At ages less than $15\cdot10^6$yr, the bulk of the lyman luminosity is provided by the hot (T_{eff}=30–50kK) Pauldrach stars, which are present in both the old and the new grid.
Apart from the differences mentioned above, the grids are identical within a factor of 2–3. At reduced resolution (no spectral line complexes) the differences are even far smaller.

8 Description of the IDL modules

8.1 CREATE_PAUL_BASE

Module CREATE_PAUL_BASE establishes the Pauldrach common wavelength grid. All unique wavelengths appearing in any of the Pauldrach models are added to this list, resulting in 1688 unique wavelengths at present. All Pauldrach models will be rebinned onto this common grid (see module REBIN_T_RATIO).

8.2 READ_PAUL_IN

Module READ_PAUL_IN differs from MICE module READ_PAUL in that it does not convert Pauldrach's wavelength scale into Rydbergs, but rather preserves the original grid in units of Angstrom.

8.3 FLUX_TO_T_RATIO

Module FLUX_TO_T_RATIO converts SED flux densities into the ratio $T_{rad}(\lambda)/T_{eff}$, using the T_{eff} of the input SED. $T_{rad}(\lambda)$, the radiation temperature, is computed from the Planck function.
The wavelength grid remains unchanged. The flux-to-T-ratio conversion is not trivial within IDL, because even in double precission the computations are confined to the range -10^{-38} to $+10^{+38}$. The approximations used to overcome this problem add no uncertainty whatsoever to the resulting T-ratio SED.

8.4 REBIN_T_RATIO

Module REBIN_T_RATIO linearly interpolates a T-ratio SED onto the common Pauldrach wavelength grid (created by module CREATE_PAUL_BASE).

8.5 POLATE_GLOG

Module POLATE_GLOG interpolates between two T-ratio SEDs, using their respective log(g) values as weighting factors. A warning message is issued when the two models not only differ in log(g) but also in T_{eff}. Since both T-ratio SEDs have the same wavelength grid, the interpolation can be done simultaneously for all wavelengths.
Two interpolation methods have been set up: one that linearly interpolates T-ratio and one that linearly interpolates *log*(T-ratio). The first method is described by the following formula:

$$TRatio\{\lambda, log(g) = g\} = TRatio\{\lambda, g_1\} + (g - g_1) \cdot \frac{TRatio\{\lambda, g_2\} - TRatio\{\lambda, g_1\}}{g_2 - g_1}$$

Here the indices 1 and 2 refer to T-ratio SEDs 1 and 2, with log(g) values g_1 and g_2. The second method is described by the following formula:

$$LOG(TRatio\{\lambda, log(g) = g\}) = LOG(TRatio\{\lambda, g_1\}) + (g - g_1) \cdot \frac{LOG(TRatio\{\lambda, g_2\}) - LOG(TRatio\{\lambda, g_1\})}{g_2 - g_1}$$

Why interpolate linearly in log(g) and not linearly in g?
Which interpolation method is to be prefered: the one in which T-ratio is interpolated or the one in which log(T-ratio) is interpolated?

8.6 POLATE_TEFF

Module POLATE_TEFF interpolates between two T-ratio SEDs, using their respective T_{eff} values as weighting factors. A warning message is issued when the two models not only differ in T_{eff} but also in log(g). Since both T-ratio SEDs have the same wavelength grid, the interpolation can be done simultaneously for all wavelengths.
Two interpolation methods have been set up: one that linearly interpolates T-ratio and one that linearly interpolates *log*(T-ratio). The first method is described by the following formula:

$$TRatio\{\lambda, T_{eff} = T\} = TRatio\{\lambda, T_1\} + (T - T_1) \cdot \frac{TRatio\{\lambda, T_2\} - TRatio\{\lambda, T_1\}}{T_2 - T_1}$$

Here the indices 1 and 2 refer to T-ratio SEDs 1 and 2, with T_{eff} values T_1 and T_2. The second method is described by the following formula:

$$LOG(TRatio\{\lambda, T_{eff} = T\}) = LOG(TRatio\{\lambda, T_1\}) + (T - T_1) \cdot \frac{LOG(TRatio\{\lambda, T_2\}) - LOG(TRatio\{\lambda, T_1\})}{T_2 - T_1}$$

Why interpolate linearly in T_{eff} and not linearly in log(T_{eff})?
Which interpolation method is to be prefered: the one in which T-ratio is interpolated or the one in which log(T-ratio) is interpolated?

8.7 T_RATIO_TO_FLUX

Module T_RATIO_TO_FLUX converts a T-ratio SED into a flux density SED, using the T_{eff} of the T-ratio SED. Flux conservation is checked by integrating over the entire spectrum, comparing the resulting flux with the predicted flux. When necessary, fluxes are multiplied by a flux correction factor.
SEDs can be written to file in three different formats: the Pauldrach format (readable by routine READ_PAUL and READ_PAUL_IN), the MICE format (readable by routine READ_MODEL) and the STARS format (readable by the STARS97 code and by READ_STARS_INTERN).

8.8 CREATE_PAUL_KUR_GRID

Module CREATE_PAUL_KUR_GRID creates the *Pauldrach* grid and the *Pauldrach-Kurucz transition* grid. Options are: linear or logarithmic interpolation and STARS97, MICE or Pauldrach type SED output files. The method used to create the grid is described in Sections 2 & 3.

8.9 INTEGRATE_HYBRID

Module INTEGRATE_HYBRID computes the flux contained within any user specified flux range for all grid SEDs at once. The resulting IDL structure serves as input structure for module SHOW_INTEGRATE.

8.10 SHOW_INTEGRATE

Ratios like F_{lyc}/F_{bol} or F_{HeI}/F_{bol} can be plotted as a function of grid parameters T_{eff} and log(g). The IDL input structure has to be generated by module INTEGRATE_HYBRID.

9 Figures

Using routine INTEGRATE_HYBRID and SHOW_INTEGRATE it was possible to display selected flux ratios as a function of position (T_{eff} & log(g)) in the "log" grid. The following ratios are displayed as an appendix to this document:

— L_{HI}/L_{bol}
— L_{HeI}/L_{bol}
— L_{NeIII}/L_{NeII}

The first and second ratio are shown in a contour plot, the third ratio in a surface plot. The lowest displayed T_{eff} is 16kK, the lowest displayed log(g) is 2.5. Note that for T_{eff} >19kK the models at log(g)=4.5 and 5.0 are identical to those at log(g)=4.0.