Stellar Populations as Building Blocks of Galaxies
Proceedings IAU Symposium No. 241, 2006
A. Vazdekis & R. F. Peletier, eds.

doi:10.1017/S1743921307007442

Metallicity and age of M31 globulars from automated fits to theoretical spectra

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Abstract. We are calculating stellar spectra for types A through K using Kurucz codes, Castelli models, and Kurucz laboratory lines plus guessed identifications for other lines in the spectra. Weighted coadditions of these spectra are being constructed to match spectra observed in integrated light of old stellar systems such as elliptical galaxies and globular clusters. Grids of theoretical spectra, both stellar and composite, that include an enhancement of light elements and span a wide metallicity range will be calculated over 2200Å – 9000Å, and will be archived on MAST at the Hubble Space Telescope website. Here we summarize our results and describe how we automate the fit to our grid of an observed high-resolution stellar or globular-cluster spectrum, to determine the stellar parameters or to break the age-metallicity degeneracy.

Keywords. stars: fundamental parameters, galaxies: star clusters, Local Group

We are constructing theoretical templates for comparison with spectra of the integrated light of old stellar systems such as globular clusters and galaxies, to constrain their ages and metallicities. This work was begun at mid-ultraviolet (UV) wavelengths in NASA and Hubble Treasury programs with B. Carney, B. Dorman, E. Green, W. Landsman, J. Liebert, R. O'Connell, R. Rood, and R. Schiavon, and extended to the near-UV and optical regions with J. Brodie, J. Strader, and the SAGES group at Lick.

We first use Castelli & Kurucz (2003) models and programs to calculate spectra of stars of all types found in old stellar systems, and match these to real high-resolution stellar spectra in which individual lines are discerned. We iteratively change the atomic transition probabilities line-by-line and guess identifications and parameters for weak lines seen in the stars but not measured in the laboratory, until we fit all relevant theoretical stellar spectra. We then combine them with appropriate weights to form composite spectra to match the integrated spectral light of old stellar populations.

Our grids of stellar spectra span types A to K, and are calculated for metallicities from one two-hundredth solar to about three times solar and for both scaled-solar and "α-enhanced" abundance mixes. In the latter, O, Mg, Si, Ca, and Ti abundances are raised by a factor of three relative to iron (as seen in Milky Way halo and bulge populations).

Both stellar and composite spectral grids will be archived with MAST at the Space Telescope Science Institute. Also included will be colors and line-strength indexes (e.g. those on the Lick system) based on the theoretical spectra, plus atlases showing theoretical fits and line identifications for high-resolution observed spectra of standard stars.

The **advantages** of theoretical spectra include:

1) Complete coverage of parameter space. Included are [Fe/H] > 0 and both α-enhanced and scaled-solar mixes, and all types of old stars, even rare and remote ones.

2) A consistent metallicity scale for stars, globular clusters, and galaxies. The same techniques and line lists are used for all.

3) Flux-calibrated spectra. Since the spectral calculations provide fluxes natively, their coaddition to form composite spectra is equally valid at all wavelengths, and produces the fractional contributions from each coadded stellar type at every wavelength.

4) Flexible resolution. The spectra are calculated at very high resolution, and then can be degraded as desired to match instrumental broadening and object velocity dispersion, and/or convolved with filter or bandpass functions to form colors and indexes.

5) Infinite S/N and zero stellar parameter uncertainty. Errors are systematic instead.

Wherever the spectral match is excellent, our theoretical spectra provide templates for use with high-resolution spectra. From them emerge parameters of old stars and of globular clusters, whose internal velocity dispersions are low ($\leqslant 15$ km s^{-1}). At high resolution, in some wavelength regions the true continuum can be discerned and individual weak lines are resolved. These set the metallicity once the stellar or giant-branch temperature is fixed, by determining the relative strengths of low-excitation and high-excitation lines of iron-peak elements. Peterson, Dorman, & Rood (2001) describe this and other purely spectroscopic methods of stellar parameter determination. The age of globular clusters follows by comparing blue and red spectral regions to establish the temperature of the turnoff stars, after taking into account the presence of hotter stars such as BHB's and blue stragglers (see below).

One must choose with care the spectral region for parameter determination, avoiding telluric lines and substantial molecular absorption. In cool giants and in globular clusters of greater than one-third solar metallicity, wavelengths redward of about 6200Å are affected by weak but numerous CN lines. The 5600Å − 6200Å region seems best, for the continuum is often visible, and lines are weak and minimally blended, as seen in Figure 1.

To automate the determination of stellar temperature and metallicity, a visual inspection of a region such as that shown in the figure is compared to theoretical spectral calculations in a grid to choose a starting point in that grid. The temperature is estimated from iron-peak lines of low versus high excitation, and [Fe/H] from Fe I and Fe II. The latter and the profiles of the wings of strong lines fix the surface gravity. Microturbulent velocity is set accordingly, as Castelli, Gratton, & Kurucz (2003) have shown it to depend primarily on stellar temperature and gravity according to the strength of convection, and others have confirmed such trends in both dwarfs and giants.

Grid spectra around these parameters are then chosen at three adjacent [Fe/H] values, using two or three [α/Fe] values for each [Fe/H]. Note that our spectra use Castelli & Kurucz (2003) models in which [α/Fe] was explicitly incorporated into the calculation of the stellar atmosphere. This is essential in giants of one-third solar metallicity and higher, for which Peterson, Dalle Ore, & Kurucz (1993) showed that the adopted [α/Fe] significantly affects the structure of the stellar atmosphere through the contribution of electrons by magnesium. A chi-squared fit or a cross-correlation of the observed spectrum versus each theoretical template then provides a quantitative measure of the goodness of fit, which in turn indicates the stellar parameters and their correlations and uncertainties.

This procedure places very stringent demands on the quality of the template spectra. To avoid minimizing to fit erroneous portions of the spectra, one must mask the worst-fitting regions, and those affected by observational flaws. One must also reliably measure the observed spectral resolution.

Current **limitations** of our theoretical composite spectra are these:

1) Their application is valid only for old systems, $\geqslant$ 1Gyr, due to the range of stellar standards for line-list calibration.

2) Some spectral regions are not yet matched theoretically in strong-lined stars. Metal-poor stellar spectral fits are satisfactory from 2200Å through 9000Å. However, at solar [Fe/H] the regions 2600Å − 3000Å are not yet well reproduced in dwarfs, nor is 3500Å − 4100Å matched in giants, largely because of unidentified weak lines.

3) Methods to quantify the uniqueness of the spectral matches have yet to be fixed.

4) Coaddition weights remain uncertain. This applies equally to empirical templates.

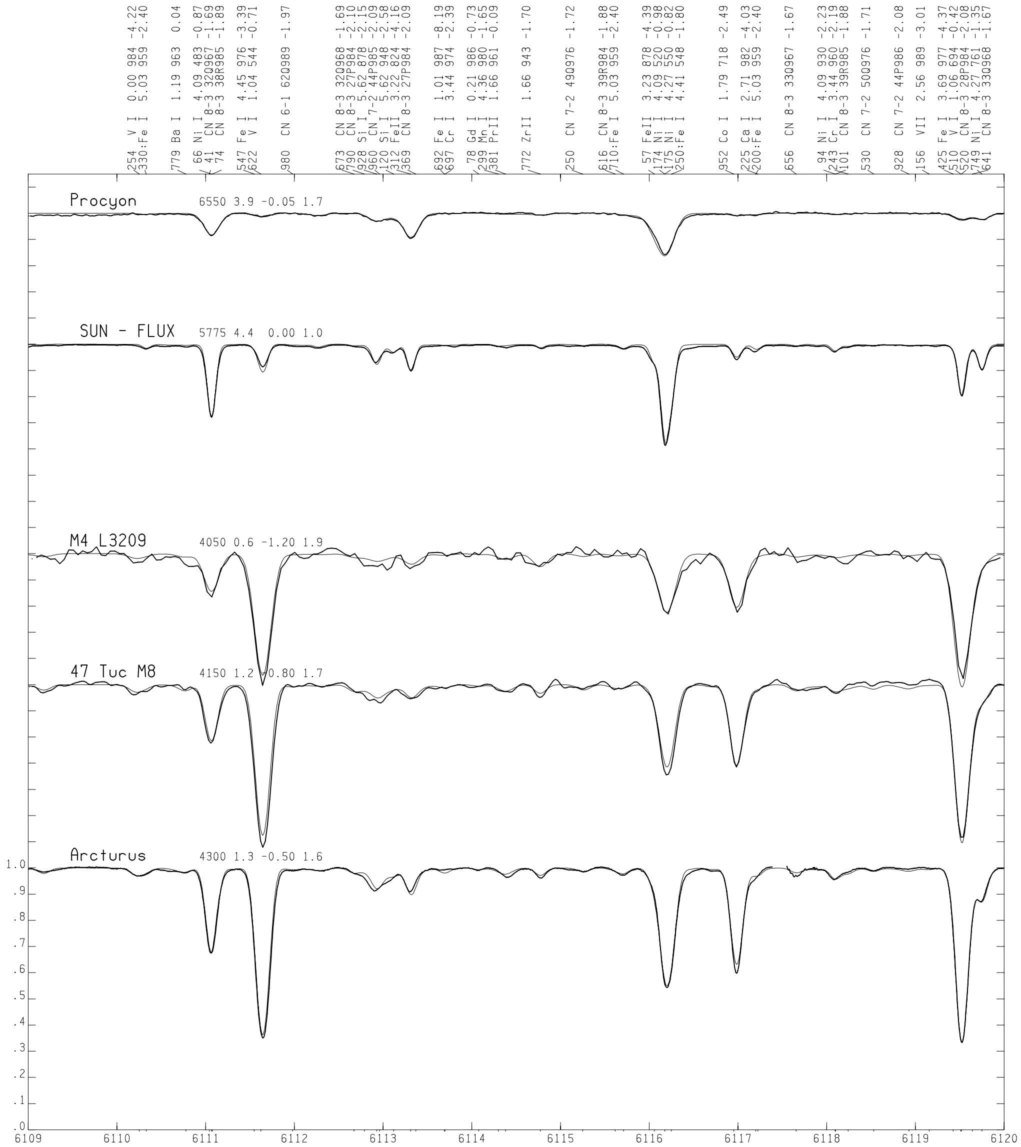

Figure 1. Each panel plots the observed spectrum of a star as a heavy line and its normalized theoretical spectrum as a light line, and gives the atmospheric model effective temperature, log gravity, [Fe/H], and microturbulent velocity after each stellar identification. Wavelength in Ångstroms is indicated along the bottom. Ticks on the left represent 10% of the full normalized flux. Line identifications are on top: the three decimal digits of the wavelength in Å are followed by the species, its lower excitation (or molecular band), the decimal digits of the residual intensity of the line in the unbroadened theoretical spectrum, and the line gf value. **Note the large change in strengths** of low-excitation lines in the top two stars versus the bottom three. Examples are V I at 6111.622Å and 6119.510Å, and Co I at 6117.952Å. In contrast, high-excitation lines of Ni I at 6111.066Å and 6116.174Å are only moderately stronger in the giants, and the Fe II line at 6113.312Å is actually weaker. The Sun and Procyon are both warm stars near the main sequence, while the bottom three stars are all cool giants: two are in the globular clusters M4 and 47 Tucanae, and the third is the K giant standard Arcturus. These giants are all metal-poor, with [Fe/H] = −1.2, −0.8, and −0.5 respectively. Even they show CN lines, whose strengths grow roughly as the square of the abundance, and also depend on oxygen abundance through formation of CO. CN suppresses the continuum in cooler stars and at higher abundances.

In the coaddition to form a composite theoretical spectrum, the weight assigned to each theoretical stellar template is currently constructed from star counts made from observational color-magnitude diagrams (CMD's) of Milky Way globular clusters. Each weight represents the number of stars in the CMD region in the range of the stellar model times the square of the radius of the typical star there. These weights are altered when the observed composite spectrum contradicts the theoretical one, which can be due to mass segregation in the cluster, and to stochastic variations in short-lived stellar types such as stars at the tip of the red-giant branch. Also uncertain and highly variable is the occurrence of stellar types such as blue horizontal branch (BHB) stars and blue stragglers (on or near the main sequence but above its turnoff), whose numbers cannot yet be predicted from theoretical tracks of single stellar evolution.

This proved critical to matching the archival HST flux-calibrated spectrum of the M31 globular cluster G1. Peterson *et al.* (2003) showed that the observed mid-UV flux levels were too high unless hot BHB stars were incorporated. Line-strength mismatch in the near-UV suggested that cool BHB's were present as well. As the metallicity of this globular is one-third solar, this result was somewhat surprising. Milky Way globulars at that metallicity only have BHB stars if they are very close to the center of the Galaxy, but G1 is far removed from the center of M31. Cool BHB's had been spotted at the magnitude limit of the M31 G1 CMD by Rich *et al.* (1996), but hot ones were missed as they fall below that limit.

Indeed, our fitting experience so far suggests that in galaxies, flux-calibrated spectra are virtually essential to break the age-metallicity degeneracy. Only then can one pin down both the relative contribution of giants versus dwarfs, and the temperature (and thus the age) of the turnoff stars themselves. Spectral of as broad a wavelength range as possible are helpful, to isolate the individual contributions from blue stragglers and BHB stars. Further discussion of these points may be found in Peterson *et al.* (2003).

Acknowledgements

Support for this work from NASA S-92512-Z, NASA NAS5-02052, and STScI GO-9455 awards is gratefully acknowledged.

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Discussion

ROSE: How can you tell how much the discrepancies at, and redward, of Hδ are caused by problems in modelling SiH as opposed to problems in modelling CN?.

PETERSON: [Si/H] makes a significant contribution redward of the bandhead at 4096Å for giants with $T_{eff} \leqslant 4500$K and [Fe/H]$\geqslant -0.7$. To check, look for the onset of extra absorption redward of the bandhead. See the Arcturus figures for an example.

Heap: We find that Castelli's model Hδ_A spectral index fits observations pretty well, but that D4000, which falls blueward of the SiH band, is poorly fit by the model.

Peterson: The Castelli model fluxes do include SiH, as the SiH predicted lines are all included in the opacity distribution functions used to generate the models. Blueward of ∼4100Å, I am still in the process of rectifying remaining "missing lines" in Arcturus: lines appear in its spectrum that are not in the Kurucz laboratory list. Such missing lines are likely a contributor to the mismatch of D4000, as their numbers tend to give towards in the blue. Once Ca*II* dominates, they become less relevant.

Gustafsson: Your suggestion that the effects of granulation on CNO abundances are on the order of 0.2 dex in Population II subdwarfs agree fairly well with results from contemporary 3D models by Asplund et al. The result I discussed by Collet et al. (2006) was for extremely metal-poor stars with [Fe/H] ∼-5.

Peterson: Thank you for this clarification.

Scott Trager (left) speaking to Ariane Lançon.