Dating intermediate-age populations with main-sequence A and F-type stars

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Abstract. The rest-frame UV spectrum of intermediate-age stellar populations is dominated by the UV flux of F-type stars at the main sequence turn-off. The UV spectrum is mostly degenerate in terms of effective temperature and metallicity, but we found two spectral indices that allow a discrimination between these two parameters. The first index measures mainly the strength of Mg I 2852, while the second index is the mid-UV color. We find that the Mg I index is sensitive to the effective temperature, but insensitive to metallicity; the UV color is sensitive to both metallicity and $T_{\text{eff}}$. We apply these indices to a sample of F stars observed with HST/STIS.

1. Introduction

While young stellar populations are characterized by massive OB stars and old populations have a typical age similar to the age of the Galaxy, intermediate-age populations span a range from a few $10^8$ years to several $10^9$ years. The total light of these stellar populations is dominated in the ultraviolet by the brightest main-sequence (MS) stars and by red giant branch (RGB) stars in the optical and in the infrared. The stars at the turn-off point on the main sequence provide a direct way to date the stellar populations. Stellar evolution theory indicates that stars in a mass range from about $4 M_\odot$ (late B-type) to $1.25 M_\odot$ (late F-type) are exhausting their hydrogen core in this intermediate-age range. Therefore, we will be able to date these populations from MS stars if we are able to derive reliably the fundamental stellar parameters (especially the effective temperature) of MS A-type and F-type stars from their ultraviolet spectrum. Although one might argue that the optical spectrum of these stars
provides better spectral diagnostics (e.g. Balmer lines), we will concentrate in this paper on their UV spectrum alone, because the composite optical spectrum reflects mainly the spectrum of the RGB stars.

After reviewing briefly the dating techniques of MS stars, we shall discuss the analysis of the UV spectrum of main-sequence F-type stars. The main difficulty is an effective temperature–metallicity degeneracy of the UV spectrum. To tackle this problem, we have obtained high-quality mid-UV spectra of a sample of F stars with STIS aboard HST. A detailed analysis of Mg I and Mg II resonance lines provide a partial solution. Finally, we shall estimate the expected accuracy in the derived effective temperatures and ages from detailed analyses of the UV spectrum and compare them with a detailed analysis of the optical spectrum (Edvardsson et al. 1993).

2. Dating methods

Most papers devoted on stellar age determinations focused on a single method, and little comparison of the different techniques is available in the literature. We recently undertook such a comparison about the age determination of MS stars (Lachaume et al. 1999). Gustafsson (these proceedings) also presents a brief review of the different techniques and discusses their accuracies. We will shortly summarize these two papers here.

Lachaume et al. (1999) showed that the method of choice for A and F stars is based on isochrones in the HR diagram. For most stars (close to 80% of their sample), a meaningful age could be derived with a typical uncertainty of the order of 30%. Gustafsson (these proceedings) estimates that the error is typically somewhat lower, about 20%. Even very accurate (one to few percents) stellar parameters yield large uncertainties on the age because the evolution on the main sequence in the HR diagram is slow. Therefore, our goal is to derive an estimate of the effective temperature from the UV spectrum as accurate as possible.

For later spectral types, the problem worsens so much that the isochrone technique becomes impractical. Stellar activity provides then the best age criterion (e.g., Ca II line core emission). Stellar activity declines with age as the star spins down. The rotation period can thus be used as an alternate age indicator, at least when stars are older than 10^8 years. Surface chemical abundances (e.g., Li, Th) have also been used as age criteria, but they suffer from various problems: lithium transport in stellar envelopes and atmospheres is not well understood, while thorium lines are heavily blended. Finally, the stellar kinematics and overall metallicity may provide a rough lower limit of the age (i.e., Pop. II stars are old).

3. The UV spectrum degeneracy

Fig. 1 illustrates the degeneracy of the mid-UV spectrum of main-sequence F stars. At high-resolution (Δλ = 0.1 Å, top panel), a metal-poor, late F star has a UV spectrum that resembles very closely the spectrum of a metal-rich, early F star. Smoothing the spectra to a resolution of 3 Å that is typical of the data recorded for high-redshift galaxies, almost no differences are apparent in
Figure 1. UV spectrum degeneracy in terms of effective temperature and metallicity. The bottom panel presents flux ratios relative to the solar composition, 6500 K model (dotted: metal-rich, 7000 K model; line-dotted: metal-poor, 6000 K model).

the whole mid-UV spectrum (middle panel). Cooler stars have steeper mid-UV flux, but this temperature effect is mimicked by higher heavy-element opacities in metal-rich stars. Notice that the λ2640 spectral break is completely degenerate!

Spectrum ratios (bottom panel) indicate the largest differences. They are found in the core of Fe II resonance lines, in the Mg I λ2852 resonance line, and above about 3000Å. The flux in the core of Fe II resonance lines is very low and these line cores would thus not be well suited in analyzing low-flux, distant galaxies. Models do not reproduce well the range, λλ2900 – 3100Å (Kurucz 1992, Heap et al. 1998). Based on these predicted flux ratios, the Mg resonance lines appear therefore to be the most promising UV spectral features to break this degeneracy.

4. Modeling the UV Mg resonance lines

First, we checked our capability to reproduce the observed line profiles of the Mg I and Mg II resonance lines with a high-resolution STIS spectrum of HD 107113. We have adopted the parameters from the Edvardsson et al. (1993) study: $T_{\text{eff}} = 6400$ K, $\log g = 4.1$, [Fe/H] = $-0.54$, and a LTE model atmosphere calculated with ATLAS9 (Kurucz 1991). Adopting the atomic parameters of the
Mg lines listed in the most recent Kurucz line list (Kurucz CD-ROM 23), the predicted Mg λ2852 line assuming LTE is too broad compared to the observed profile. Fitting the line would require reduction of log $gf$ from 0.27 to about 0.00, which is incompatible with all recent atomic structure calculations. An alternate solution is to decrease the Van der Waals broadening constant. Kurucz lists log $\gamma_{vdW} = -7.09$, while a simple estimate made with the impact approximation (see Gray 1992) yields log $\gamma_{vdW} = -7.78$. This estimate is supported by a recent calculation (Barklem, priv. comm.) yielding log $\gamma_{vdW} = -7.592$. We are able to match the observed line profile with the impact approximation value. We have adopted this new value, because this seems a much more likely explanation of the mismatch than an incorrect gf-value.

Is this the correct explanation, or is the failure to match the Mg λ2852 line due to our adopting LTE? This question is legitimate for strong UV resonance lines, even in such cool MS stars. We would indeed expect that NLTE Mg overionization might result in weakening Mg I lines. We have therefore performed a NLTE Mg line formation calculation with our NLTE model atmosphere code TLUSTY (Hubeny & Lanz 1995). We kept the temperature and density structures from the ATLAS9 model, and recalculate only the NLTE populations of Mg. We have used 13 and 11 level model atoms for Mg I and Mg II, respectively. Several excited levels are grouped into the highest superlevels. The NLTE line formation calculation yields a slightly stronger Mg λ2852 line and, thus, does not solve the mismatch. This results from an overpopulation of the ground state of Mg$^0$. No differences were found in the Mg II resonance line profiles, except in the very cores, which are anyhow affected by chromospheric activity. The wings of the Mg II resonance lines are formed in layers with densities large enough to ensure an applicability of LTE.

While departures from LTE are small, we also found that the Mg II resonance line profiles were still poorly reproduced. In particular, the LTE and the NLTE calculations yield a predicted flux which is too high in the near-wing regions ($\Delta \lambda \approx 1 - 3$ Å) and too low in the far wings ($\Delta \lambda > 3$ Å). This is a typical signature of the assumption of complete redistribution in frequency (CRD) that is usually made in most synthetic spectrum calculations. In CRD, there is no correlation between the frequencies of absorbed and emitted photons in a spectral line. In reality, the line scattering process is a combination of CRD and of coherent scattering (CS), with a branching ratio dependent essentially on density. This approach is known as partial redistribution (PRD) (Mihalas 1978). With respect to CS, CRD results in an increased emission near the line core. When photons are absorbed in the line wings, they have a large probability to be reemitted in the core and to be scattered in the core subsequently. We have implemented a simplified case of PRD for the Mg resonance lines, the partial coherent scattering approximation (Hubeny 1985). When PRD is included, the Mg II resonance lines are indeed well matched. Small changes are also found in Mg λ2852.

Fig. 2 displays the best model fitting the STIS spectrum of HD 107113. The best fit is obtained for [Mg/Fe]$= +0.05$, a slightly lower abundance ratio than the value derived by Edvardsson et al. (1993). However, a later study (Tomkin et al. 1997) suggested that the Mg abundances derived by Edvardsson et al.
Figure 2. Matching the HST/STIS spectrum of HD 107113 (thick histogram line). Top panel: Mg I λ2852 line; middle and bottom panels: Mg II lines (the thin line is the best model).

were slightly overestimated. Notice in the bottom panel that the subordinate Mg II λ2791, 2798 lines are also well matched.

Could we use the Mg I and Mg II lines as a $T_{\text{eff}}$ indicator, as seems obvious at first glance? We computed a series of models with different effective temperature to check this point. Cooler models predict a similar decrease in the flux of Mg I and in Mg II resonance lines! Therefore, the line flux ratio is not a good $T_{\text{eff}}$ estimator. This behavior comes from the continuum opacity which is dominated by the contributions of neutral heavy elements.

5. Separating Age and Metallicity

While the Mg I to Mg II line ratio does not provide a good $T_{\text{eff}}$ indicator, Fig. 1 still suggests that a region around $\lambda 2850$ is sensitive to $T_{\text{eff}}$. Moreover, a region around $\lambda 2770$ behaves in the opposite way. We have therefore defined a Mg I [2850]/[2770] line strength index in a way similar to a line equivalent width. The line index is defined as $(1 - f_{2850}/f_{2770})$, where $f_{2770}$ and $f_{2850}$ are flux averages in two 20 Å-wide passbands centered at these wavelengths. In Fig. 3, we combine this index with a mid-UV color index defined as a difference between two magnitudes calculated with 30 Å-wide passbands at [2310] and [3040]. We have computed these two indices for a series of model atmospheres covering a
range in effective temperature (5500 to 7500 K) and in metallicities (one tenth to ten times solar). Fig 3 shows that the Mg I index is mainly sensitive to $T_{\text{eff}}$ while the mid-UV color is sensitive to both metallicity and $T_{\text{eff}}$. The two indices provide a way to break the effective temperature-metallicity degeneracy.

We have measured the Mg I and the mid-UV color from HST/STIS spectra of 8 F-type stars. Fig. 3 indicates that we are indeed able to discriminate between the three metal-rich stars and the five metal-poor stars in our sample. We derive the effective temperature and metallicity of each star by bi-linear interpolation in the model grid. A close examination shows that our effective temperatures are on average about 200 K larger than the estimates made from optical colors by Edvardsson et al. (1993). Moreover, the Mg I index is also sensitive to the adopted Mg abundance, or more precisely to the Mg/Fe abundance ratio. If we vary this ratio by ±0.2 dex, the derived $T_{\text{eff}}$ vary by about ±200 K. Because it is unlikely that all 8 stars are Mg-poor, our analysis so far yields a systematic overestimate on $T_{\text{eff}}$, or an underestimate of the age of a stellar population. Missing opacity sources in the model atmospheres may provide an explanation of this systematic effect. The uncertainty in the UV spectral analysis is also larger than the typical estimated error from optical colors (typically, $\Delta T_{\text{eff}} \approx 50 - 100$ K).
6. Conclusion

We have shown that the effective temperature-metallicity degeneracy of the UV spectrum of F stars is the most serious hindrance to derive the age of an intermediate-age population from its rest-frame UV spectrum. So far, solar metallicities have been assumed to derive effective temperatures and ages. We have defined two new indices that break this degeneracy, although some systematic errors may remain. The accuracy is lower than in the optical range, and the results are sensitive to the Mg/Fe abundance ratio. How serious are these problems for deriving the age of stellar populations from the UV spectrum?

First, we note that chemical evolution models indicate that metallicity close to solar is quickly reached. Second, the Mg/Fe ratio depends on the IMF slope—a steeper IMF results in more SN I (Fe enrichment), while a flatter one results in more SN II (Mg enrichment). The Mg/Fe abundance ratio seems correlated to the total mass of the galaxy, spanning a ±0.3 dex range (Peletier 1999). Third, our typical error appears to be of the order of 200 K. This corresponds to an error in age of about 5×10^8 years. A systematic age underestimate may be of the same order.

Despite the remaining uncertainties, these new indices should allow to decide between high and low age estimates of the population in the high-redshift galaxy, LBDS 53W091 (Spinrad et al. 1997; Heap et al. 1998). Unfortunately, no Mg I spectral feature is visible in LBDS 53W091 spectrum, probably due to difficulties in sky line corrections.

References

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