

Where is the Information Located in Stellar Spectra?

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ABSTRACT

Using theoretical stellar flux distributions, I have calculated the sensitivities of stellar colors to changes in T_{eff} , $\log g$, and $[\text{Fe}/\text{H}]$, as functions of wavelength. The primary conclusions are:

- **The spectral region below the Balmer jump provides unique information about the temperatures of OB stars and the gravities of A-K stars.** A broad-band “*u*” filter, lying entirely below the Balmer jump, and covering approximately 2800–3600 Å, would add important capabilities for WFC3 observations of resolved stellar populations.
- A *u* filter would also provide high sensitivity to metallicity in stars of type F and later, in cases where the luminosity is known separately.
- For stars of type A and later, the region around 4000–4500 Å also contains information on stellar metallicities, which can be separated from the gravity effects at shorter wavelengths. The *B* filter and/or a filter similar to Strömgren *v* would provide this information.
- As is well known, a color index formed from two longer-wavelength filters, such as *V* and *I*, provides temperature information that is fairly independent of metallicity and gravity.
- A narrow-band filter pair to measure the equivalent width of $H\beta$ would add more capabilities for measuring temperatures and gravities of O, B, and A stars.

1. Introduction

The Wide Field Camera 3 (WFC3) will provide the *Hubble Space Telescope* with powerful new capabilities in wide-field imaging in the near-ultraviolet region of the spectrum. WFC3 should be particularly useful in studies of resolved stellar populations in galaxies.

As input to decisions about the filter complement and CCD coatings for the optical channel of WFC3, I have prepared the following discussion of the regions of the spectrum that contain information about the basic parameters of stars: the effective temperature (T_{eff}), surface gravity ($\log g$), and metallicity ($[\text{Fe}/\text{H}]$).

Most of this discussion will already be quite familiar to stellar astronomers, but nevertheless I believe some useful conclusions will emerge.

2. Explanation of the Calculations and Plots

All of the plots presented here are based on the library of theoretical stellar flux spectra assembled by Lejeune, Cuisinier, & Buser (1997). In the temperature range considered here, Lejeune et al. have based their library primarily on the models of Kurucz (1995), but they have applied wavelength-dependent corrections to the theoretical spectra so that they predict broad-band colors that agree empirically with observations. See Lejeune et al. for full details of their correction procedures.

I have extracted individual corrected theoretical spectra from their library in order to explore the sensitivity of stellar energy distributions to changes in the fundamental parameters, T_{eff} , $\log g$, and $[\text{Fe}/\text{H}]$. In all of the plots shown below, I vary one of these parameters while holding the other two constant. Then I plot the resulting change in magnitude as a function of wavelength. Specifically, the wavelength-dependent magnitude difference is defined as

$$\Delta\text{mag}(\lambda) = -2.5 \log[F_{\lambda,2}(\lambda)/F_{\lambda,1}(\lambda)] + \text{const},$$

where $F_{\lambda,1}(\lambda) = F_{\lambda}(\lambda; T_{\text{eff},1}, g_1, [\text{Fe}/\text{H}]_1)$ is the spectral energy distribution for model 1 whose effective temperature, surface gravity, and metallicity are $T_{\text{eff},1}$, $\log g_1$, and $[\text{Fe}/\text{H}]_1$, respectively, and $F_{\lambda,2}(\lambda)$ is defined similarly for model 2. I always set the constant such that $\Delta\text{mag} = 0$ in the V band, i.e., at 5550 Å.

I then plot $\Delta\text{mag}(\lambda)$ vs. wavelength over the range 2000–10,000 Å.

To understand the plots, the reader should note that **if the delta magnitude curve is flat around zero over a certain wavelength interval, then there is no information**

in that wavelength interval about the stellar parameter that was changed.

3. The u Filter

In the discussion below, I will refer repeatedly to a hypothetical broad-band filter whose bandpass lies entirely shortward of the Balmer jump, i.e., $\lambda < 3650 \text{ \AA}$. For convenience, I will call this filter a “ u ” filter.

However, my u filter should not be confused with the ground-based Strömgren or Gunn u filters, which have relatively narrow bandpasses since they are limited at the short-wavelength end by the atmospheric cutoff. From space there is no reason not to get better throughput by using a much wider bandpass, say roughly 2800–3600 \AA , or even wider if possible as long as there is no throughput above the Balmer jump. (The ability to fabricate such a filter may, however, be limited by red leaks.)

4. Temperature Sensitivity

I begin by considering the wavelength bands that contain information about stellar effective temperatures.

4.1. OB Stars

Fig. 1 shows the magnitude differences that result from changes in T_{eff} in O- and B-type stars. In each case, I have taken a main-sequence star ($\log g = 4.5$) of the effective temperature indicated in the plot, increased the temperature by 1000 K, and calculated the resulting $\Delta\text{mag}(\lambda)$ as a function of wavelength. (At 40,000 K I had to use $\Delta T_{\text{eff}} = +5000 \text{ K}$ at $\log g = 5$, due to limited model availability at these high temperatures.)

Fig. 1 shows that the curves are nearly flat at $\lambda > 3800 \text{ \AA}$. In other words, when the temperature is increased, the flux increases by virtually the same amount throughout the optical spectrum, leading to virtually no change in the color. This illustrates the well-known fact that *optical colors are insensitive to effective temperatures for O and B stars* (because we are on the Rayleigh-Jeans tail throughout the optical band at these temperatures).

There is, however, temperature information below 3600 \AA , as Fig. 1 reveals. Over the 12,000–20,000 K range, the size of the Balmer jump depends upon T_{eff} , in the sense (as Fig. 1 shows) that increasing the temperature decreases the size of the jump. Even for

O-type stars near 40,000 K, there is still temperature sensitivity if one were to combine a broad-band filter lying entirely below 3600 Å (e.g., the u filter described above) with at least one filter longward of 3600 Å.

Note that I have ignored interstellar reddening throughout this discussion, and this would of course be an issue for OB stars. However, the behavior of the Balmer jump is different from that of interstellar extinction, so it should be possible to disentangle the two effects if enough different filters were used (e.g., a filter that measured the 2200 Å interstellar feature would be extremely valuable). Note also that there is temperature information in the equivalent widths of the hydrogen Balmer lines (see discussion below of the utility of an H β filter).

In particular, in a case where the stars were in a galaxy of known distance, and thus of known luminosity, addition of a u filter to the WFC3 complement would provide a capability of measuring stellar temperatures (and hence of inferring evolutionary states) in resolved populations. Such a capability is not easily available longward of the Balmer jump (other than through the changes in the Balmer lines, shown in Fig. 1, which would require narrow-band filters or spectra).

4.2. A through K Stars

Fig. 2 shows the magnitude differences that result from changes in T_{eff} of 500 K, at constant gravity and metallicity in A-type dwarfs. At 10,000 K most of the optical band is still insensitive to temperature changes, since we are still on the Rayleigh-Jeans tail. However, there is good temperature sensitivity below about 4000 Å. At 9000 K we are beginning to get temperature sensitivity throughout most of the optical band, so that at this temperature (and below) the conventional temperature color indices such as $B - V$, $V - I$, etc., become useful.

Fig. 3 shows the temperature sensitivities for cooler stars. As is well known, optical colors such as $B - V$ and $V - I$ are excellent temperature indicators for such stars. The calculations are for a temperature change of only 250 K.

5. Gravity Sensitivity

For many applications in stellar-population studies, the gravity (i.e., luminosity) need not be determined if the distance to the target is known independently. However, when the distance is not known, or if the membership of the target in the galaxy is uncertain, then

$\log g$ becomes a crucial quantity. For example, several new types of standard extragalactic candles would become available to *HST* with addition of a gravity-sensitive filter, including Population II post-AGB stars and the extremely luminous yellow supergiants of Population I. A direct measurement of the distance to the Coma cluster using the latter stars should be possible with WFC3.

5.1. OB Stars

Fig. 4 shows the effect of varying the gravity at constant temperature (indicated in the figure) and solar metallicity, in B stars (O stars behave similarly to the 25,000 K curve). The colors have only a weak gravity dependence below the Balmer jump, and virtually no dependence above the jump. Note that the sign of the Balmer-jump dependence reverses between 15,000 and 10,000 K.

There is, however, considerable information about the surface gravity in the equivalent widths of the Balmer lines. A wide/narrow filter pair that measured, say, the strength of $H\beta$ would provide gravity information, but of course would have low throughput.

5.2. Cooler Stars

Fig. 5 shows that, beginning around 9000 K and extending to cooler stars, the size of the Balmer jump is extremely sensitive to gravity. At 8000 K, for example, the $u - V$ color changes by 1 magnitude for a reduction of $\log g$ by 2 dex. This is the well-known behavior exploited by Strömgen photometry, and is a powerful argument for a u filter on WFC3. Note, incidentally, the flux redistribution preferentially to wavelengths just above the Balmer jump, giving a color index like $u - B$ an additionally enhanced gravity sensitivity.

Fig. 6 shows that the short-wavelength sensitivity to gravity changes continues into cooler stars. At 4000 K the sensitivity starts to be due to changes in metallic-line opacity rather than changes in the Balmer jump.

We thus see that *a u filter would be sensitive to surface gravity for all stars from type A to K.*

6. Metallicity Sensitivity

Finally I turn to the sensitivity of stellar colors to changes in the metallicity.

6.1. OB Stars

Fig. 7 shows the effect of changing the metallicity from solar to 1/100 solar ($[\text{Fe}/\text{H}] = -2$) in O- and B-type main-sequence stars. (The behavior for the two chosen temperatures is typical of that throughout the OB spectral types.) As the figure shows, there is little dependence of the colors of hot stars upon metallicity, except for a small effect on the Balmer jump in late B stars, and below about 2500 Å for hotter stars.

6.2. Cooler Stars

The metallicity behavior for cooler giants is shown in Fig. 8. Around type A0 ($\sim 10,000$ K) there is still little change in color, except below 3000 Å. However, as is well known, at later types substantial “ultraviolet excesses” arise at low metallicity. A filter such as Johnson *B* or Strömgren *v* is useful for isolating the metallicity color changes at about 4000–4500 Å from gravity changes in the *u* band. However, if the luminosity is known separately, the *u* band is itself an extremely powerful metallicity indicator (note the expanded magnitude scale for this plot).

REFERENCES

- Kurucz, R. 1995, private communication to Lejeune et al.
Lejeune, T., Cuisinier, F., & Buser, R., 1997, A&AS 125, 229

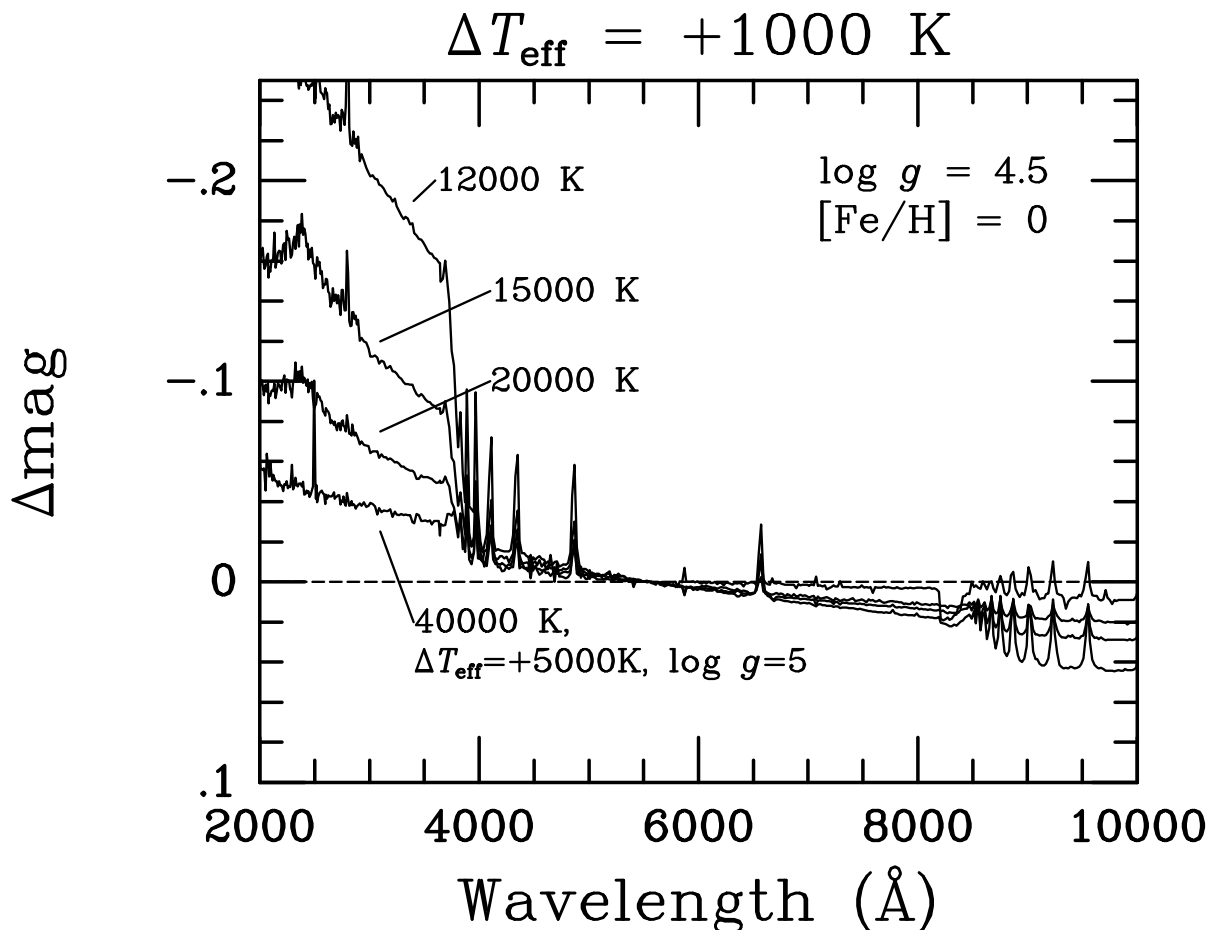


Fig. 1.— Delta magnitude plots for O and B stars of the indicated effective temperatures. In each case, the magnitude changes are those resulting from an increase in T_{eff} of 1000 K, at fixed main-sequence $\log g$ and solar metallicity (except at 40,000 K where the available models were limited as noted in the figure). The magnitude differences are nearly flat across the optical band, indicating little color sensitivity to changes in T_{eff} . However, there is significant temperature sensitivity below the Balmer jump, even in O-type stars. **Availability of a u filter on WFC3 would add the capability of determining stellar temperatures of hot stars in resolved populations.**

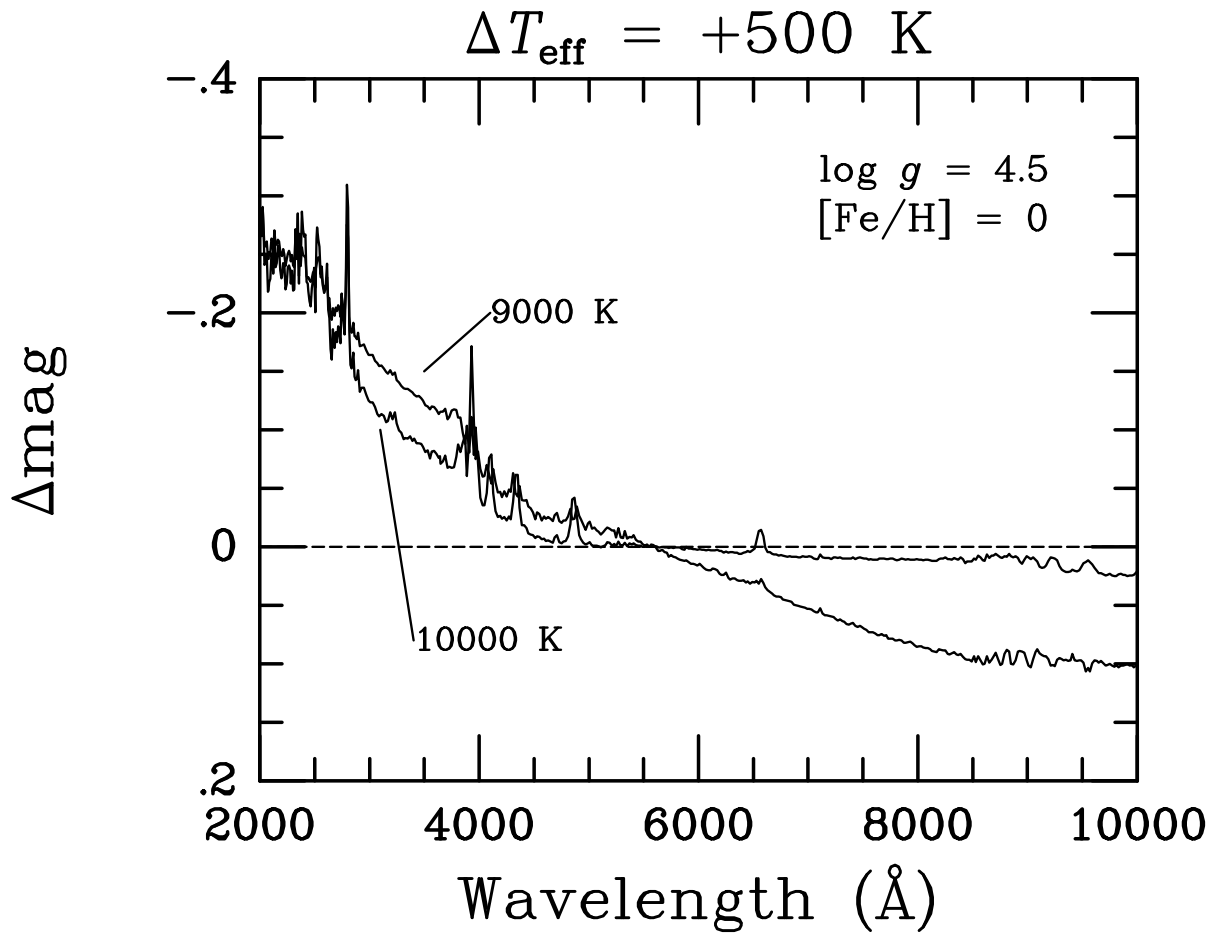


Fig. 2.— Wavelength dependence upon temperature changes in A-type dwarfs at constant gravity and constant solar metallicity. At 10,000 K most of the optical band is still insensitive to temperature changes, but there is temperature sensitivity below about 4000 \AA . At 9000 K there is temperature sensitivity throughout most of the optical band, so that conventional temperature color indices such as $B - V$ or $V - I$ become useful.

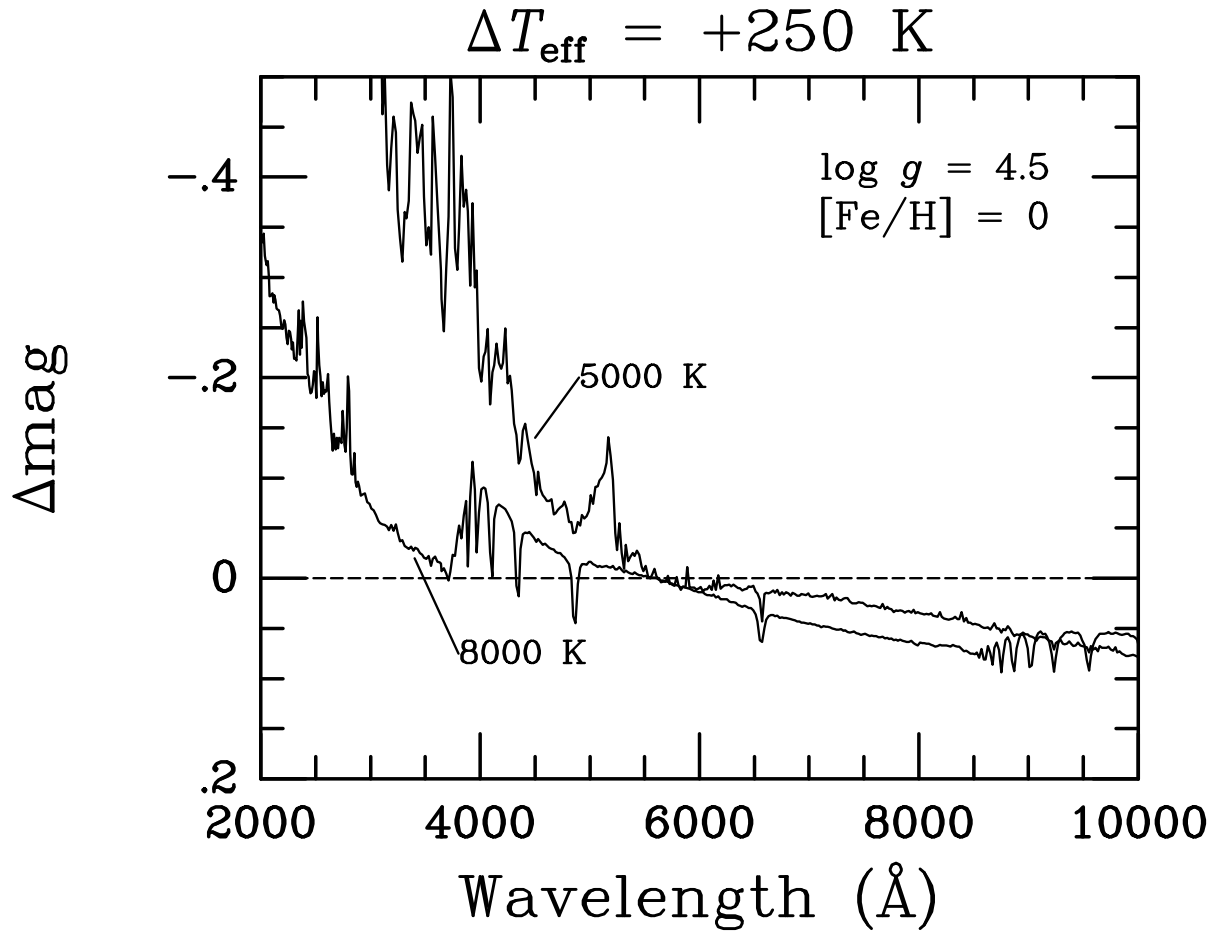


Fig. 3.— Temperature sensitivities for cooler stars. As is well known, optical colors such as $B - V$ and $V - I$ are excellent temperature indicators.

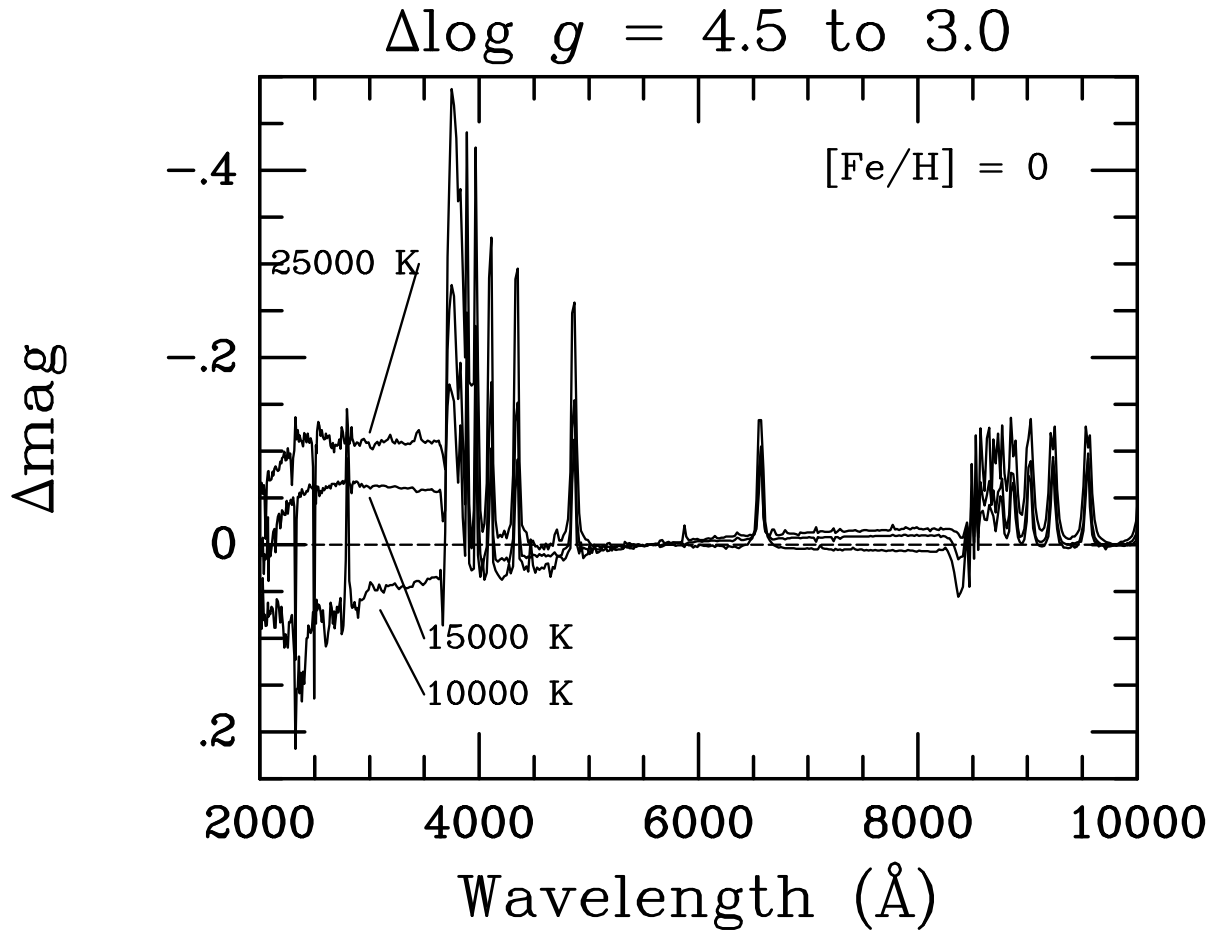


Fig. 4.— Magnitude changes resulting from varying the gravity at constant temperature (given in the curve labels) and solar metallicity in B stars. The colors have only a weak gravity dependence below the Balmer jump, and virtually no dependence above the jump. The sign of the Balmer-jump dependence reverses between 15,000 and 10,000 K. The equivalent widths of the Balmer lines are, however, extremely sensitive to $\log g$, and could be measured with a pair of narrow-band $\text{H}\beta$ filters.

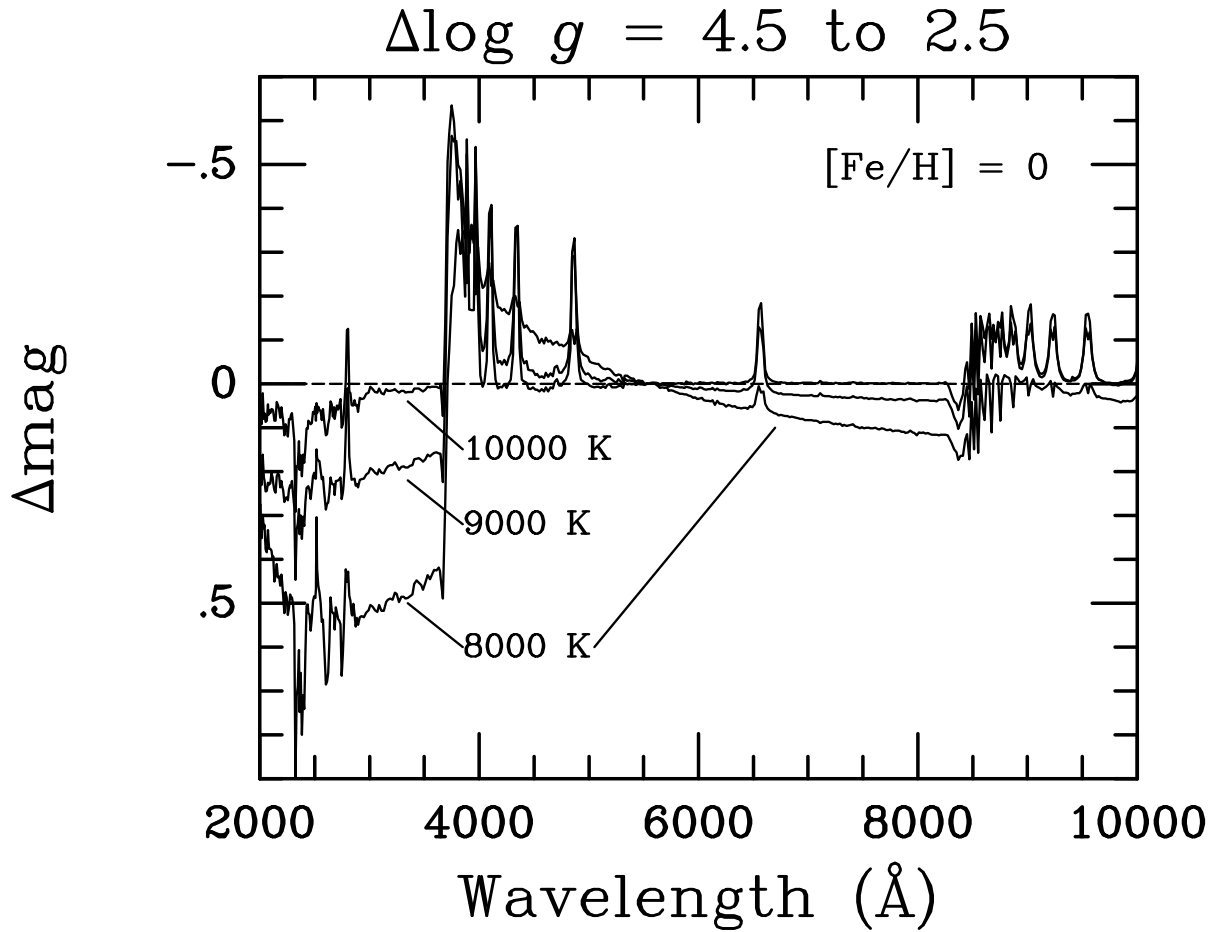


Fig. 5.— At 9000 K and cooler, the size of the Balmer jump is extremely sensitive to gravity changes, as shown in these delta-magnitude curves for $\Delta \log g = 2$ dex at constant temperature and metallicity. This is a key argument for a broad-band u filter on WFC3.

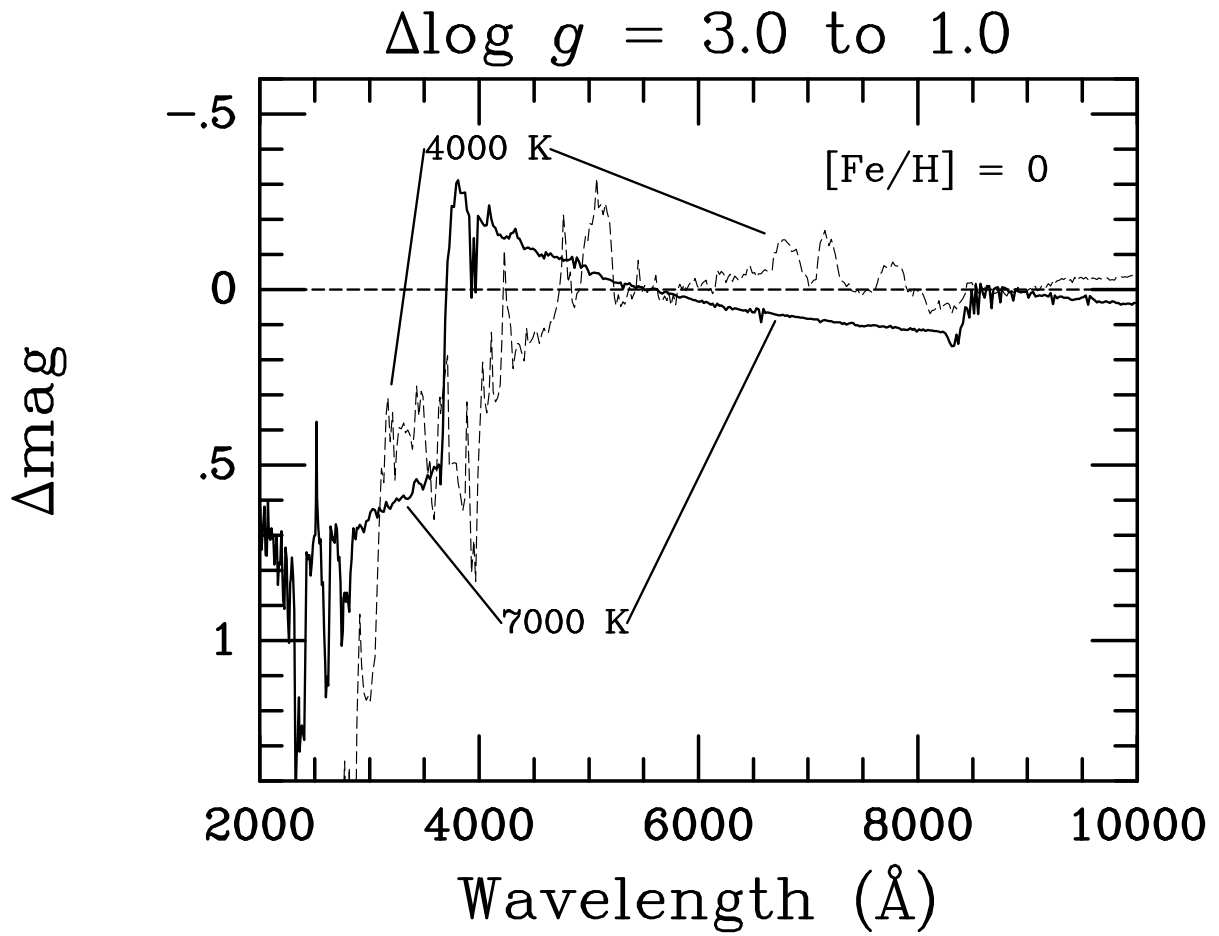


Fig. 6.— The short-wavelength sensitivity to gravity changes continues into cooler stars.

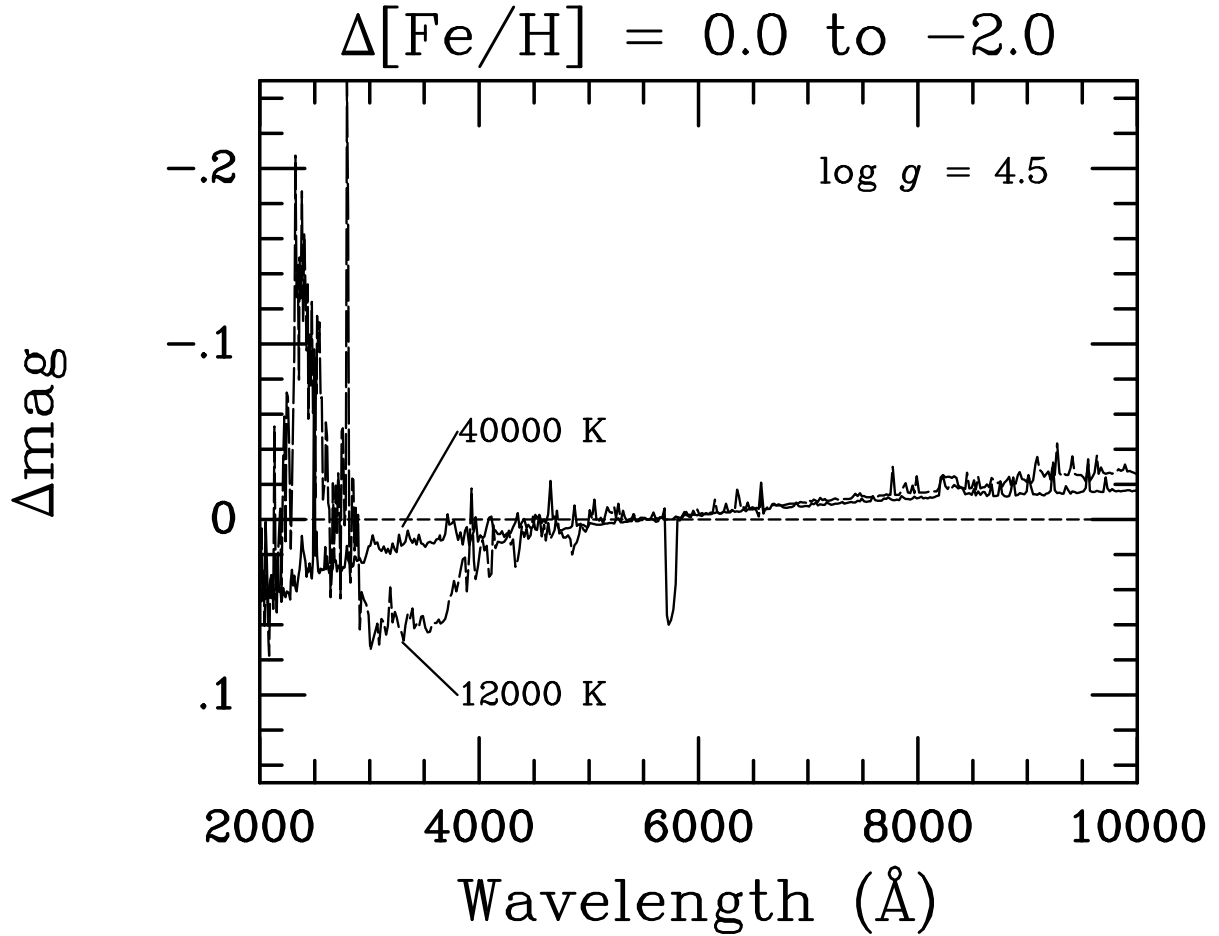


Fig. 7.— Color effects of changing the metallicity from $[\text{Fe}/\text{H}] = 0$ to -2 in O- and B-type dwarfs. There is little dependence of the colors of hot stars upon metallicity, except for a small effect on the Balmer jump in late B stars, and below about 2500 \AA for hotter stars.

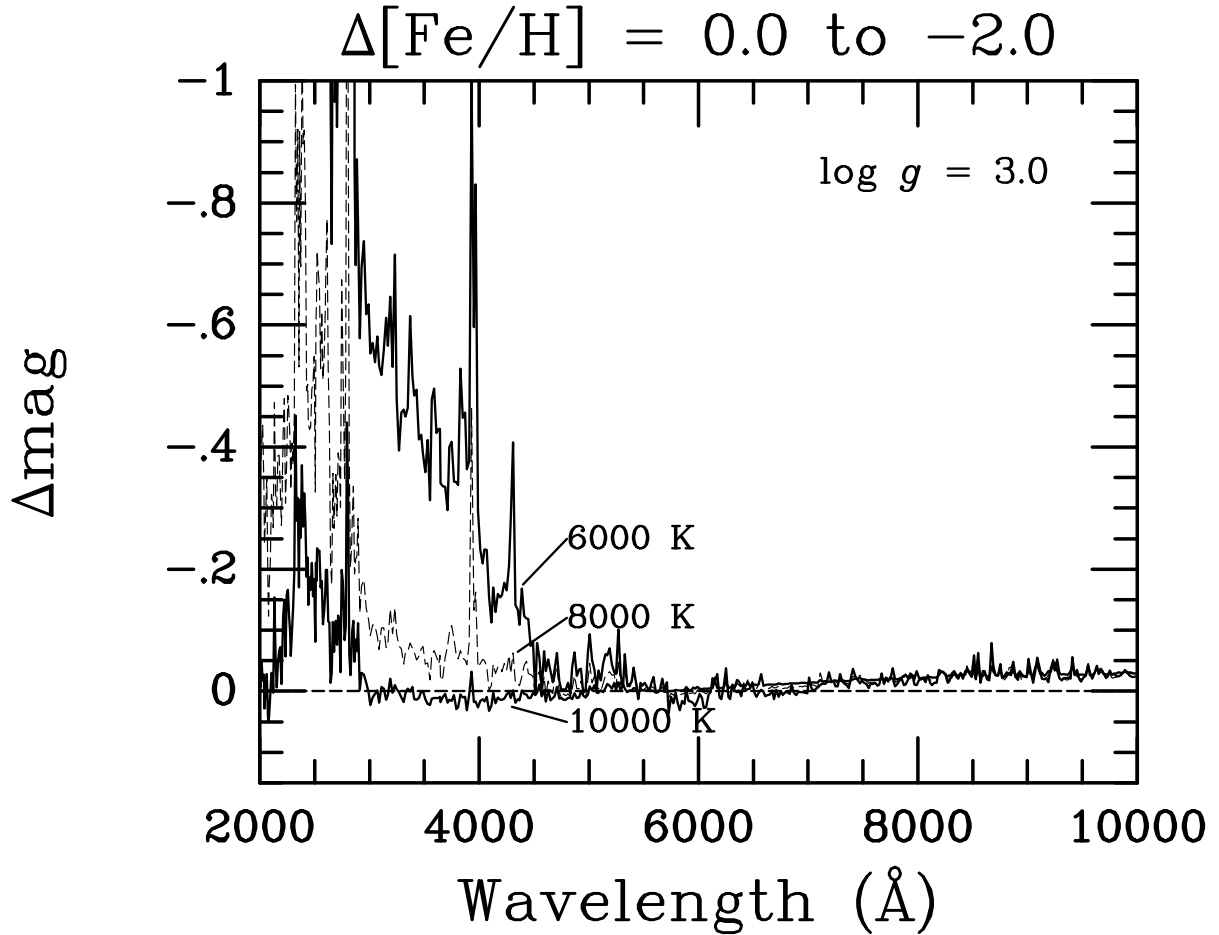


Fig. 8.— Metallicity behavior for cooler giants. Around type A0 there is still little change in color with metallicity, except below 3000 Å. At all later types, substantial UV excesses arise at low metallicity. Johnson *B* or Strömgren *v* is useful for isolating the metallicity color changes at about 4000–4500 Å from gravity changes in the *u* band. If the luminosity is known separately, the *u* band is extremely sensitive to metallicity.