The Determination of $T_{\rm eff}$ and log g for B to G stars

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Abstract. A review of the methods for determining the $T_{\rm eff}$ and $\log g$ for B to G type stars is presented. The four most-commonly used methods — photometry, spectrophotometry, hydrogen-line profiles and the Infrared Flux Method — are discussed. The $T_{\rm eff}$-$\log g$ diagram is also discussed, along with the use of fundamental stars in the calibration of model atmosphere fluxes and colours.

1. Introduction

The stellar atmospheric parameters of effective temperature ($T_{\rm eff}$) and surface gravity ($\log g$) are of fundamental astrophysical importance. They are the prerequisites to any detailed abundance analysis. As well as defining the physical conditions in the stellar atmosphere, the atmospheric parameters are directly related to the physical properties of the star; mass (M), radius (R) and luminosity (L).

Model atmospheres are the analytical link between the physical properties of the star (M, R and L) and the observed flux distribution and spectral line profiles. These observations can be used to obtain values for the atmospheric parameters, assuming of course that the models used are adequate and appropriate. The values of $T_{\rm eff}$ and $\log g$ obtained must necessarily be consistent with the actual values of M, R and L. Unfortunately, the physical properties of stars are not generally directly ascertainable, except in the cases of a few very bright stars and certain binary systems. We have to rely on model atmosphere analyses of spectra in order to deduce the atmospheric parameters.

We need to be confident in the atmospheric parameters before we start any detailed analyses. This is especially important when comparing chemically peculiar stars to normal ones. Take, for example, the recent disagreements over the atmospheric parameters of the metallic-lined (Am) stars: Smalley & Dworetsky (1993) found that the large systematic differences between the results of Lane & Lester (1984) and Dworetsky & Moon (1986) were due to metallicity effects. Hence, it is very important to ensure that the atmospheric parameters used are free from any systematic errors. These can be introduced, for example, by differences in atmospheric chemical composition, rotational broadening, interstellar reddening, the presence of a binary companion, etc.

The four most widely used methods for determining $T_{\rm eff}$ and $\log g$ are now discussed.

2. Photometry

The intensity of stellar flux varies as a function of wavelength and these variations are linked to temperature, surface gravity and chemical composition. A measurement of stellar flux at several wavelengths can be used to determine such parameters. Ideally, continuous spectrophotometric wavelength coverage through a narrow bandpass would be the preferred observations, but this is time consuming and generally only possible for relatively bright stars.

Wide and intermediate band photometric systems have been developed to describe the shape of stellar flux distributions via magnitude (colour) differences. Since they use wide bandpasses observations can be obtained in a fraction of the time required by spectrophotometry and can be extended to much fainter magnitudes. The use of standardized filter sets allows for the quantitative analysis of stars over a wide magnitude range.

By carefully designing the filter bandpasses that define a photometric system, colour indices can be obtained that are particularly sensitive to one or more of the stellar parameters. Indeed, photometric surveys of faint stars are used to identify anomalous stars which warrant much closer spectroscopic investigation. Photometric colour indices, once calibrated with model atmospheres, can be used to determine atmospheric parameters. Three photometric systems are in general use:

- The most widely used photometric system is the UBV system, developed by Johnson & Morgan (1953). The calibrations by Buser & Kurucz (1978, 1992) are worth noting. However, while UBV colours do agree well with spectral type for stars of similar composition, they do not provided for the separation of luminosity classes and are strongly affected by reddening (Johnson, 1958).
- The $uvby\beta$ system, developed by Strömgren (1963, 1966) and Crawford & Mander (1966), overcomes some of the limitations of the UBV system. Several model calibrations have been produced, including Relyea & Kurucz (1978), Moon & Dworetsky (1985), Lester, Gray & Kurucz (1986), Kurucz (1991), Castelli (1991) and Smalley & Dworetsky (1994). Moon (1985) produced two very useful programs for dereddening observed $uvby\beta$ colours (UVBYBETA) and obtaining $T_{\rm eff}$ and $\log g$ (TEFFLOGG).
- Geneva seven-colour system has been used since around 1960 at the Geneva Observatory. Calibrations include North & Hauck (1979), Kobi & North (1990) and North & Nicolet (1990).

The calibration of the $uvby\beta$ system will be discussed in a little more detail, since it is particularly suitable in the determination of $T_{\rm eff}$ and $\log g$ and a large amount of observation data is available (Hauck & Mermilliod, 1990). Raw model colours need to be matched to the standard system, which can be achieved in the following ways:

1. The most basic model calibrations are those used by Kurucz (1979, 1991). He normalizes his model colours to the observed colours of Vega. Vega was originally chosen because it is the primary flux standard with the

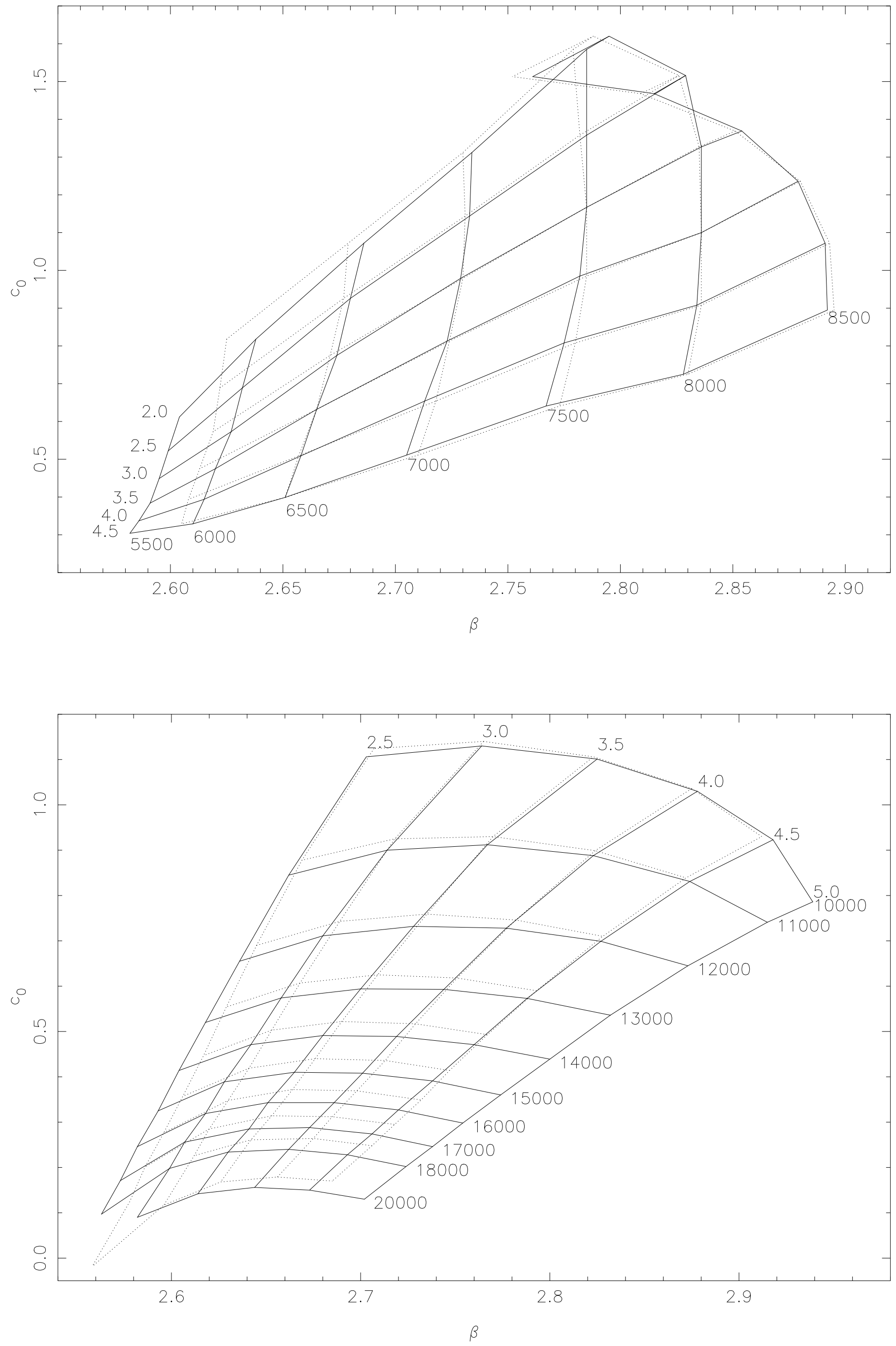

Figure 1. Examples of $uvby\beta$ calibrations. The solid lines are the grids of Smalley & Dworetsky (1994) and the dotted lines those of Moon & Dworetsky (1985).

highest accuracy spectrophotometry. However, its is now known that Vega is a metal-poor pole-on rapidly rotating star (Adelman & Gulliver, 1990; Gulliver, Hill & Adelman, 1994).

2. An extension to the Vega zero-point shift was used by Moon & Dworetsky (1985). They used stars with fundamental values of T_{eff} and $\log g$ to shift the grids in β and c_0, in order to reduce the discrepancy between the observed and predicted colours.

3. An alternative approach was used by Lester, Gray & Kurucz (1986). They treated the raw model colours in the same manner as raw stellar photometry. The model colours were placed on the standard system using the relations of Crawford & Barnes (1970) and Crawford & Mander (1966).

Ideally the Vega zero-point shift should be all that is needed. In practice, however, either or both of the other calibration procedures must be used to get a good agreement with other methods and fundamental stars. Napiwotski, Schönberner & Wenske (1993) presented a useful discussion on the use of photometry to determine the atmospheric parameters of B, A and F stars. For a discussion on Am stars see Smalley & Dworetsky (1993).

The $uvby\beta$ system has a metallicity index, δm_0, which can be used to estimate the overall metal content ([M/H]) of an A, F or G star. Several metallicity calibrations for δm_0 (and the Geneva Δm_2 metallicity index) have been produced. For A and F stars there are, for example, the calibrations by Berthet (1990) and Smalley (1993a). There are more calibrations for F and G stars, including those by Crawford (1975), Crawford & Perry (1976), Olsen (1984) and Nissen (1988). Unfortunately, the δm_0 and Δm_2 indices are no longer sensitive to chemical composition in B-type stars.

Overall, photometry can give very good first estimates of the atmospheric parameters. In the absence of any other suitable observations, the atmospheric parameters obtained from photometry are of sufficient accuracy for most purposes, with typical uncertainties of ± 200 K and ± 0.2 dex in T_{eff} and $\log g$, respectively.

3. Spectrophotometry

In contrast to the wide bandpasses used by photometric systems, spectrophotometry is the measurement of stellar flux through (generally) narrow bandpasses, usually over wider wavelength ranges. Only a restricted wavelength range can be observed from the ground; optical spectrophotometry generally covers 3300 $\sim$ 10000 Å. However, a lot can be determined from such spectrophotometry, since it contains the Balmer Jump and the Paschen continuum, as well as representing a large fraction of the total energy output of A and F stars (Malagnini et al., 1986). Since the emergent flux distribution of a star is shaped by the atmospheric parameters, we can use spectrophotometry to determine values for these parameters, by fitting model atmosphere fluxes to the observations. Figure 2 shows the sensitivity of the flux distribution to the various atmospheric parameters for an A-type star.

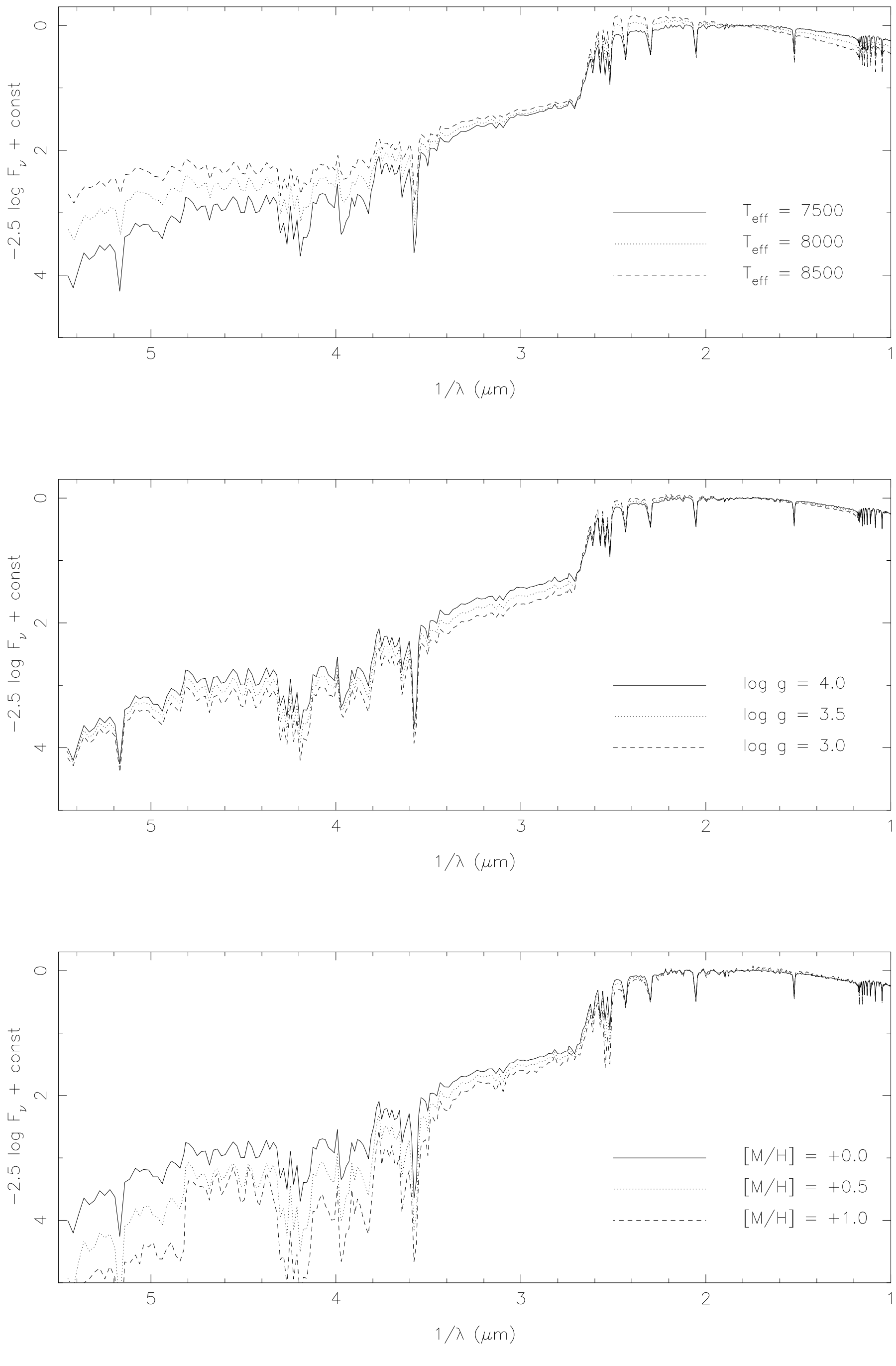

Figure 2. The sensitivity of flux distributions to $T_{\rm eff}$, $\log g$ and [M/H]. The solid line is for a model with $T_{\rm eff}$ = 7500, $\log g$ = 4.0 and [M/H] = 0.0. The dotted and dashed lines indicate models with one of the parameters adjusted, as indicated. All fluxes have been normalized to zero at 5556Å.

Optical spectrophotometry is generally placed on the Hayes & Latham (1975) absolute flux scale, with has an overall uncertainty of around ±0.02 mag. As well as the secondary standards listed by Taylor (1984), there are some very useful catalogues, including of Breger (1975), Ardeberg & Virdefors (1980) and Adelman et al. (1989). Optical spectrophotometry can be supplemented by the use of satellite observations. Ultraviolet fluxes can be obtained, for example, from the S2/68 catalogues (Jamar et al., 1976; Macau-Hercot et al., 1978) and low resolution IUE spectra. This can improve the sensitivity of the fits to chemical composition.

For normal stars spectrophotometric flux fitting allows for a good determination of $T_{\rm eff}$ (Morossi & Malagnini, 1985). However, interstellar reddening must be allowed for, since it can have a significant effect on the observed flux distribution and any derived $T_{\rm eff}$. Unfortunately, $\log g$ does not appear to be reliably determined from spectrophotometry. Malagnini, Faraggiana & Morossi (1983) for that for B stars $\log g$ was poorly determined from continuum spectrophotometry. Smalley (1992) found that even by increasing the metal abundance in the models used to fit the spectrophotometry of Am stars, the $\log g$ is still too low when compared to that obtained from photometry.

Clearly, further higher-quality spectrophotometry is required, so that spectrophotometric flux fitting can reach its true potential as an atmospheric parameter diagnostic.

4. Hydrogen line profiles

The Balmer lines provide an excellent $T_{\rm eff}$ diagnostic for stars cooler than about 8000 K due to their virtually nil gravity dependence (Gray, 1992). Theoretical profiles can be generated with Peterson's BALMER program, which uses the stark broadening tables of Vidal, Cooper & Smith (1973). By fitting these theoretical profiles to observations, we can determine $T_{\rm eff}$. For stars hotter than 8000 K, however, the profiles are sensitive to both temperature and gravity. For these stars, the Balmer lines can be used to obtain values of $\log g$, provided that the $T_{\rm eff}$ can be determined from a different method.

While the hydrogen lines are relatively free from absorption lines in most B-type stars, the same cannot be said of stars later than mid A-type. Fitting is hampered by the numerous metal lines in the spectra of these stars, ironically just as the hydrogen lines become insensitive to $\log g$! Nevertheless, by careful reductions and analysis, observations of Balmer lines can still be used to determine $T_{\rm eff}$.

Normalization of the observations is critical. Naturally, the shape of the Balmer line must be preserved (Smith & van't Veer, 1987). A useful check is to observe Vega or Sirius and compare the reduced spectrum with those given by Peterson (1969). While it is very difficult – if not impossible – to use échelle spectra, medium-resolution spectra can be used. We have to allow for the effects of blending of metal lines and the effects of rotation. Rotation is potentially a more difficult problem, since by increasing resolution we can reduce the effects of blending, but not that caused by rotational smearing. Figure 3 shows the effects of increasing [M/H] and $v \sin i$ on the apparent continuum level. By reference to synthetic spectra the location of the true continuum level can be established.

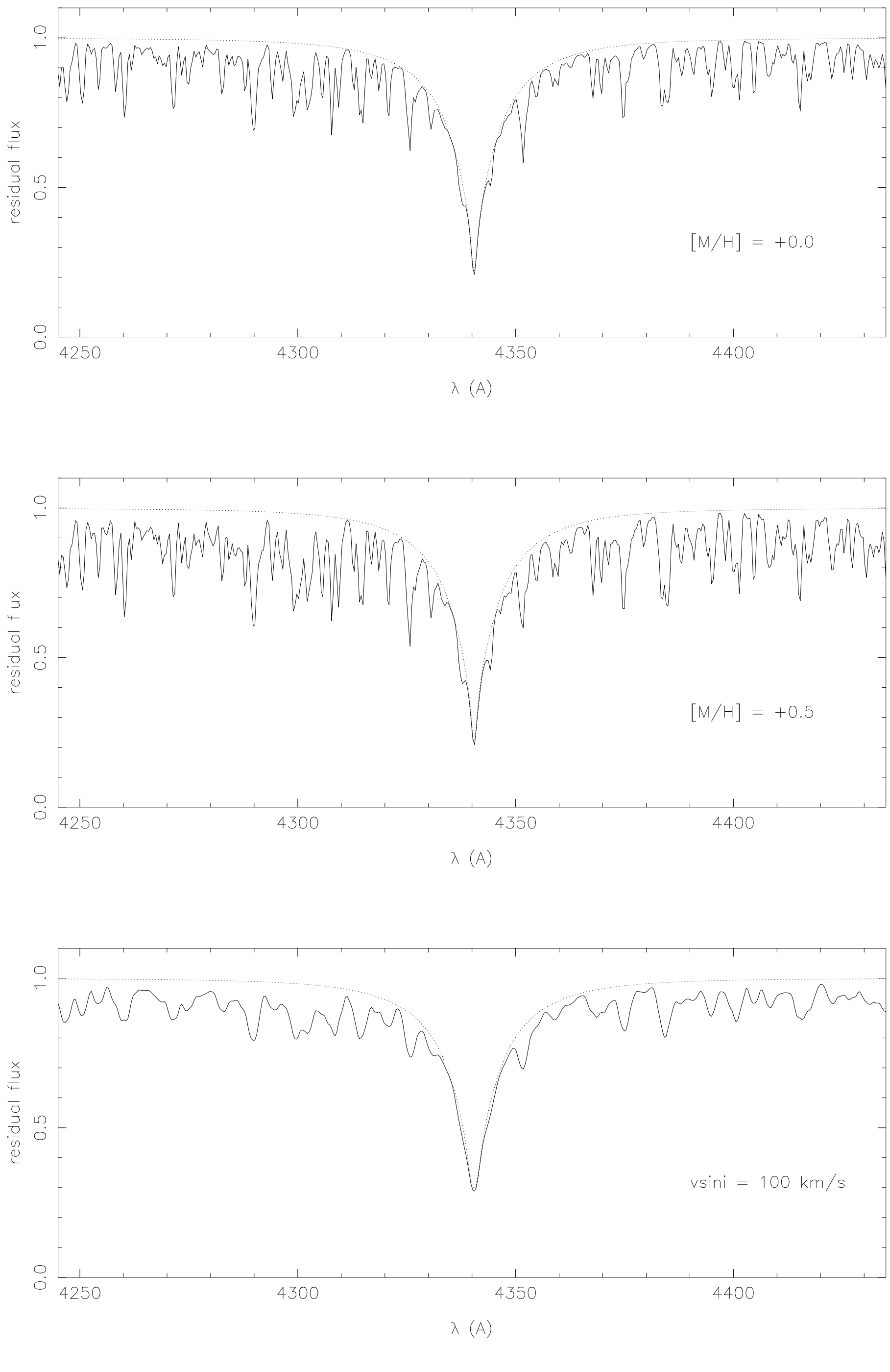

Figure 3. The effect of increasing [M/H] and $v \sin i$ on the spectrum around Hβ. These are synthetic spectra with $\mathrm{T_{eff}} = 7500$ and $\log g = 4.0$ and a simulated resolution of around 0.4Å. The true Hβ profile is shown as the dotted line.

An alternative approach to fitting hydrogen lines has been used by van't Veer, Cayrel & Coupry (1991). They use the ratio of a star's profile with respect to that of Procyon. This procedure cancels some instrumental effects and reduces the uncertainties in continuum location. Of course, the T_{eff} of Procyon has to be assumed, but it does have a fundamental value.

Overall, hydrogen lines give very good values of T_{eff} for A and F stars, with internal errors of the order of 100 K or less. But, naturally, the actual value of T_{eff} is model dependant.

5. Infrared Flux Method

The IRFM, developed by Blackwell & Shallis (1977) and Blackwell, Petford & Shallis (1980), can be used to determine T_{eff}. The method relies on the fact that the stellar surface flux at an infrared wavelength is relatively insensitive to temperature. The method is almost model independent, with only the infrared flux at the stellar surface requiring the use of models (Blackwell & Lynas-Gray, 1994; Mégessier, 1994).

The method requires a complete flux distribution in order to obtain the total integrated (bolometric) stellar flux. In practice, however, all of the flux is not observable, especially in the far-ultraviolet. But, this is only a serious problem in the hotter stars. Here model atmospheres have to be used to insert the missing flux, in order to obtain the total integrated flux. Accurate infrared fluxes are, of course, essential for this method to produce reliable results. Several direct and indirect flux calibrations have been performed (Hayes, 1979; Dreiling & Bell, 1980; Wamsteker, 1981), with the absolute flux measurements of Vega by Mountain et al. (1985) being particularly important. Gezari, Schmitz & Mead (1987) have produced a comprehensive catalogue of infrared flux measurements, including fluxes from the IRAS satellite. Blackwell et al. (1990) gave a good discussion on the IRFM.

The method is, of course, sensitive to any cool companions. The effect of the companion is to lower the T_{eff} derived for the primary. A modified method was proposed and discussed by Smalley (1992, 1993b). This method relies on the relative radii of the two components in the binary system. The effect of allowing for the companion can be dramatic; the T_{eff} determined for the primary can be increased by 200 K or more.

Given good spectrophotometry, the IRFM should give the 'best' fundamental estimate of T_{eff}, short of a 'true' fundamental value. It ought to be possible to obtain temperatures to an accuracy of 1 % or better (Blackwell et al., 1990). Provided that we do not have a companion star!

6. The T_{eff}-$\log g$ diagram

The results from the four methods discussed above can be used to construct a T_{eff}-$\log g$ diagram (sometimes called a Kiel Diagram). This is a great visualization tool, since it allows you to view the relative positions of solutions from the different methods. Using such a diagram it is easy to see how varying various other parameters, such as [M/H], affects the relative positions of the various solutions. Figure 4 shows a T_{eff}-$\log g$ diagram for the classical Am star 63 Tau.

The solar abundance results are obviously discordant. By increasing the abundance to [M/H] = +0.5 and introducing a cool companion (5000 K), a much better agreement can be obtained.

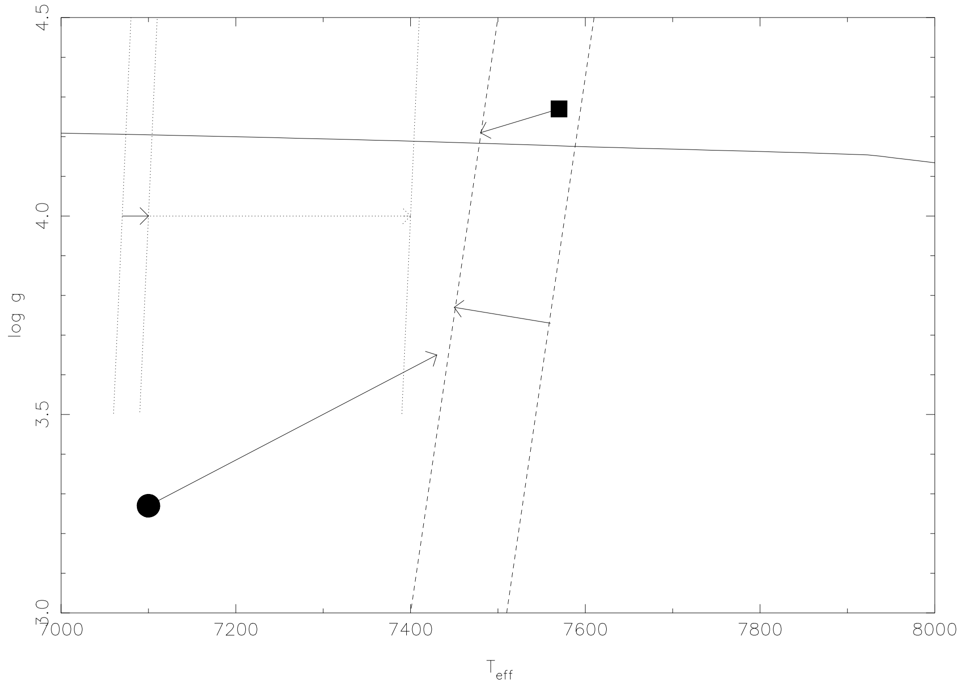

Figure 4. A T_{eff}-$\log g$ diagram for the Am star 63 Tau. The results from the four methods are shown as follows: the filled square is from the Moon & Dworetsky (1985) *uvbyβ* girds, the filled circle is from spectrophotometry, the dashed line that from fitting Hβ profiles and the dotted line the IRFM result. Photometry and Balmer lines agree very well, but are significantly hotter than the results from Spectrophotometry and the IRFM. The solid arrows indicate the effect of using [M/H] = +0.5models. Now spectrophotometry is in good agreement with photometry and Balmer line, but the IRFM is still significantly lower. However, by introducing a cool companion (5000 K) the IRFM can be brought into agreement with the other methods (dotted arrow). The solid line is the Hyades isochrone, based on the evolutionary calculations of Schaller et al. (1992). Note that the $\log g$ from spectrophotometry is significantly lower than that from photometry.

7. Fundamental Stars

A fundamental star is one in which its atmospheric parameters (or at least one) has been obtained without using model atmospheres. These are the "pins" by which the models can held in place.

Fundamental values of T_{eff} can be obtained from angular diameters and spectrophotometry (see Code et al., 1976). Angular diameters can be measured directly using interferometry (Hanbury Brown et al., 1974; McAlister & Hartkopf, 1988) or from observations of lunar occultations (e.g. Ridgway et al., 1982). The spectrophotometric requirement is the same as in the IRFM, in that a complete flux distribution is required. Often, especially in hot stars, model atmosphere fluxes have to be used to add in the contribution from unobserved far-ultraviolet flux (Code et al., 1976).

A fundamental value of $\log g$ can be obtained for a star which has a known mass and radius. Binary systems are the main source of fundamental $\log g$ values, even then we are restricted to detached double-lined eclipsing binary systems. Furthermore, for these stars to be useful in testing or calibrating model atmospheres, the two stars must be essentially identical. For a full discussion on binary systems the reviews of Popper (1980) and Andersen (1991) should be consulted.

Of all the fundamental stars, only Sirius and Procyon have truly fundamental values of *both* $T_{\rm eff}$ *and* $\log g$. This prompted Smalley & Dworetsky (1995) to review the lists of fundamental stars. They examined the fundamental temperatures obtained by Code et al. (1976) and concluded that modern data produced no significant differences. Additionally, they extended the list of stars with fundamental values of *both* $T_{\rm eff}$ *and* $\log g$, by obtaining fundamental temperatures for some binary systems. Angular diameters were indirectly inferred from the stellar radii and distances (from the parallax catalogue of van Altena et al., 1991). The extra step involved in obtaining angular diameters and the lower quality of the spectrophotometry meant that the uncertainties were much larger. Indeed, there is much scope for improvement, by using better quality flux measurements and higher accuracy distances.

Chemical composition cannot be obtained in a fundamental manner. We must use perform model-dependent abundance analyses relative to some normal or standard. The only true standard is the Sun (Anders & Grevesse, 1989). However, in order to obtain a good $T_{\rm eff}$ and $\log g$, we only need to have a good determination of the mean metal content. A good estimate of [M/H] can be obtained from photometry, for example. Once we have reliable atmospheric parameters, a detailed abundance analysis ought to give us a reliable composition. This is provided we have a good microturbulence and allow for the effects on the apparent continuum level due to blending and rotational smearing.

Overall the accuracy of the fundamental stars is lower than the internal errors of the model-dependent methods for determining atmospheric parameters. Hence, we need to significantly improve the fundamental stars, especially to improve the $T_{\rm eff}$ scale. Also, we need more chemically peculiar stars with fundamental parameters, in order to test the models of such stars.

8. Conclusion

As we have seen, the four most widely used methods of determining $T_{\rm eff}$ and $\log g$ can be used together to obtain a self-consistent solution. This is provided that the effects of [M/H], binary companions, etc. are taken into account.

Over recent years there have been considerable improvements in the area of model atmospheres. Two of the most significant have been the improved opacity in model fluxes (Kurucz, 1991) and improvements in the treatment of convection.

The work presented by Kupka at this workshop is particularly interesting. In fact, initial tests by myself and Nathan Rogers during this workshop indicate that these model colours agree very well with those of the fundamental stars. We can now be hopeful that model atmospheres are now free from large systematic errors.

In order to thoroughly test the results from model atmosphere calculations, we need improved atmospheric parameters for the fundamental stars. The "pins" need to be placed with an accuracy of 1 % or better. The current best is only 2 %, with most no better than 4 %. More importantly, we do not have enough chemically peculiar star with fundamental parameters. These are needed to ensure that the models of such stars are reliable. After all, it is the systematics that cause the greatest uncertainties; not the exact values of the atmospheric parameters.

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