FUNDAMENTAL PARAMETERS AND MODELS OF STELLAR ATMOSPHERES

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ABSTRACT. The use of photometric and spectroscopic criteria, calibrated by model-atmosphere calculations, for determining effective temperatures, surface gravities and chemical compositions of stars is illustrated and commented on. The accuracy that can be obtained today in such calibrations is discussed, as well as possible ways of improving this accuracy further for different types of stars.

1. INTRODUCTION

In a well-known quotation from the sixties Underhill describes the problem of "fitting a series of beautiful internally-consistent models to honest-to-goodness real stars that are up there" as a "horrible" one (cited by Pecker, 1965). After 20 years of progress in the study of stellar atmospheres, does this problem remain "horrible" and, if so, in which respect?

Many circumstances are important to a consideration of this question. These are related to the remarkable improvements for observational as well as theoretical studies of stellar atmospheres.

The new observational opportunities – the opening up of the vacuum ultraviolet window, in particular by the International Ultraviolet Explorer; the new or improved high-resolution spectrographs, equipped with sensitive multi-element detectors with linear and well defined responses, now used for studies in the visual and near infrared; and the extended or quite new opportunities for observations in the infrared, from the ground or higher up, at high or lower resolution – all are of utmost importance.

Another very significant circumstance is our rapidly increasing ability to carry out large-scale model calculations, and the invention of adequate numerical methods for solving the relevant equations. Thus, the formation of spectral lines and continua may now be modeled without relying on the assumption of LTE, even for relatively complex atoms; the effects of departures from plane-parallel stratification in spheri-

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cally extended or inhomogeneous atmospheres may be investigated; the
blanketing from millions of atomic and molecular spectral lines may be
considered; and even convection and its effects on the structure and the
radiation field may be modeled in a relatively self-consistent way. In
fact, the technological development in this field is so rapid that we
need truly daring minds that are willing to start formulating problems
that used to be "absolutely hopeless", if we are to take full advantage
of this drastic development.

A third circumstance of great importance is our new ability to
experimentally measure and accurately calculate a great amount of the
physical data (notably cross sections) which are necessary ingredients
in models of stellar atmospheres and in quantitative analyses of stellar
spectra.

In view of all this progress couldn't one argue that the problem
characterized by Anne Underhill is no longer horrible, but even -
solved? If we glance through the literature, we shall find that for
most stars, errors in the effective temperature estimates are now
often stated to be less than 4%, and errors in surface accelerations of
gravity and in chemical abundances, less than 0.15 dex. Isn't this
enough? No. First, because modern observational techniques and the
basic physical data should admit a significantly higher accuracy - our
understanding of the physical processes and of the structure of the
stellar atmospheres, i.e., our model-building is often nowadays the
limiting factor. An improvement in this understanding would then make
further progress possible in many fields of astronomy where stellar
atmospheres are studied more as probes into the structure or chemical
history of our Galaxy, than as physical systems. Secondly, many recent
studies have revealed that stars are complicated systems - some of them
may even be more complicated than the Sun, which is a shocking thought
for any student of solar physics. The models are based on, and presently
have to be based on a number of simplifying assumptions. The same
assumptions therefore underlie the determination of fundamental para-
meters using these models, and also (in most cases) the error estimates
for these parameters. Thus, we have to live with an uncomfortable
feeling that even if our fitting procedure of a stellar spectrum to a
calculated one looks satisfactory and self-consistent, the fundamental
parameters of the real stars may be astonishingly different from those
of the model. It is a major task for research in this field to try to
investigate to what extent this sceptical attitude is relevant.

There is also a third important reason why one should not be satis-
fied with the seemingly rather small errors in the determination of fun-
damental parameters. This reason will be discussed in Sec. IV, below.

In the present review we shall concentrate on the determination of
effective temperatures, surface gravities and chemical abundances by
using model atmospheres. Thus, we shall not dwell on the determination
of micro - or macro turbulence parameters or magnetic field strengths or
other (probably) secondary parameters, nor shall we comment on the
determination of angular momentum, which may be a primary parameter for
the star itself and certainly is of significant importance for the
structure of its atmosphere.

In Sec. II some general comments will be made, while Sec. III reviews the situation for stars of different spectral types. This review will mainly concentrate on "normal stars", although the reader should observe the interesting development that presently is taking place in the study of Wolf-Rayet stars (e.g. DeLoore and Willis 1982, Smith and Willis 1982, Underhill 1983), of hot subdwarfs (Heber et al. 1984, Schönberner and Drilling 1984) and planetary nebula nuclei (Méndez et al. 1983), of early main-sequence stars with peculiar abundances (Cowley and Adelman 1983, Renson 1981) and, not least, of white dwarfs (Sion et al. 1982, Koester et al. 1982, Wegner and Yackovich 1983).

2. SOME GENERAL REMARKS

When estimating the <u>effective temperature</u> of a star from properties of its emitted radiation one uses the continuous flux distribution or temperature-sensitive spectral lines. In principle, these features are not direct measures of the total emissivity per stellar surface area, as is the effective temperature, but rather they measure the temperature in the flux-forming layers. However, in many applications such as in abundance analysis, this characteristic temperature is the relevant quantity to use for estimating the number densities of the atomic or molecular state under consideration. In this case "T_{eff}" is more to be regarded as a label of the relevant model to combine with the star of interest than a measure of the surface flux.

An obvious way to derive T_{eff} is to compare flux gradient measures, obtained from scans or colors, with the corresponding calculated quantities. This procedure is non-trivial in practise, as several other contributions to this symposium will indicate. In addition to the problems with the absolute calibration of the observational system there are theoretical difficulties in calculating the blocking effect from spectral lines in the band-passes observed. The problem is aggravated, for most spectral types, by the fact that the line-blocking gets heavier as the wavelength gets shorter, while, on the other hand, the temperature sensitivity of the (quasi-) continuous flux curve is greater at shorter wavelengths. Thus, for any given problem, a deliberate compromise has to be made as regards which wavelengths to choose - a compromise where practical circumstances, like how easy it is to achieve an absolute calibration of the system proposed, are also of obvious significance.

An important alternative to the flux gradient method is "the integrated flux method" of Blackwell and Shallis (1977), Blackwell et al. (1979). Although first applied to G-K giants it has recently been used extensively for stars of early types (cf. Underhill 1982, and references cited therein, Remie and Lamers 1982) and for very late giants (Tsuji 1981a and b). These applications are natural since the easily measurable gradients of the flux distributions of O and early B stars are not very temperature sensitive, while the visual spectrum of M stars and carbon stars is too heavily blocked by molecular lines to admit any accurate continuum difinition. Following the "multiplicative" formulation of the method of Tobin (1983) we may write

$$\sigma \, T_{eff}^4 \;\cong\; \int_{\lambda_1}^{\lambda_2} f_\lambda \; d\lambda \;\cdot\; \frac{\int_0^\infty F_\lambda(T_{mod}) \; d\lambda}{\int_{\lambda_1}^{\lambda_2} F_\lambda(T_{mod}) \; d\lambda} \;\cdot\; \frac{F_{\lambda'}(T_{mod})}{f_{\lambda'}} \;\cdot$$

Here, f_λ is the observed flux corrected for extinction and (in the first factor) integrated between the wavelengths λ_1 and λ_2, which should span a considerable wavelength interval. F_λ is the calculated physical flux from a model atmosphere with effective temperature T_{mod} and λ' a relatively long wavelength. Such a choice of λ' is claimed to be of importance since the line-blocking there is generally smaller and the interstellar reddening is less. Of major significance is that $F_{\lambda'}$ is little sensitive to the temperature structure of the model. Thus, we arrive at an iterative procedure, where in iteration i $T^{(i)}(mod) = T_{eff}(i-1)$. It is convergent (although one should be careful in checking that full convergence has really been obtained, cf. Remie and Lamers 1982 and Tobin 1983). The final result is generally not very model dependent, at least as long as the wavelength interval (λ_1, λ_2) contains most of the radiation emitted.

The use of temperature sensitive spectral lines for determining effective temperatures – such as measurements of the ionization of hydrogen through the Balmer lines for F stars, the excitation equilibrium of neutral iron for G-K giants or TiO bands for late K dwarfs –often requires a good grasp of the line-forming process, including broadening mechanisms, and reliable atomic or molecular data. If the lines to be used are formed at different depths in the atmosphere, which is often the case, e.g. when ionization equilibria are to be used, detailed knowledge about the temperature structure may also be necessary.

A broad review of effective-temperature determinations has been provided by Böhm-Vitense (1981a).

Spectroscopic and photometric determinations of surface gravities are based on the different pressure sensitivity of different sources of opacity in neighboring spectral regions. Well-known examples are the Stark-broadened wings of the Balmer lines in early-type stars (i.e., of the opacity in the wings relative to the continuum), the different pressure sensitivity of the absorption on the opposite sides of the Balmer discontinuity for F-type stars, the pressure sensitivity of ionization equilibria, the strength of damping wings of strong metal lines relative to corresponding weak lines in red giants and subgiants, and the strengths of molecular lines (such as those of MgH relative to MgI lines) in late-type stars. As will be illustrated below, these different methods have quite different properties as regards their sensitivity to the uncertainties in the model atmospheres.

As to the determination of chemical abundances there are strong general arguments for preferring weak spectral lines, situated along the linear part of the curve-of-growth if they are measurable. This is the case not merely because the strengths of these unsaturated lines are

independent of line broadening and various shortcomings in the theory thereof, but also because these lines are formed at great depths where the departures from LTE often are smaller than at more shallow atmospheric depths. Moreover, the strength of the weak lines is more insensitive to model uncertainties (cf., e.g., the discussion concerning abundances of metal-poor stars by Gustafsson, 1983). However, for fainter objects one often has to rely on theoretical or semi-empirical calibrations of relatively strong lines or complex spectral features. Examples of such measures are given by Carbon et al. (1982), Cohen (1982) and Thévenin and Foy (1983), and such measures are also represented in most photospheric systems.

Sometimes there may even be no measurable lines available at all for crucial elements; this is the case for e.g. the electron donors in the atmospheres of cool He-rich white dwarfs. In such cases, at the very best, quite indirect methods are available, and it may be that the final determination of fundamental parameters is not unique (Wehrse 1984).

The determination of chemical abundances for stars was discussed at an ESO workshop (Nissen and Kjär, 1980) and at the IAU General Assembly in Patras 1982 (see Gustafsson, 1983, and several other papers in the same volume of the P.A.S.P.).

The presentation above has been artificially divided into the discussion of determination of various parameters, one at a time. In practice, however, any observable quantity responds to changes of several model parameters and sometimes even does so in a remarkably non-linear way. Neglect of these effects may lead to significant errors in derived parameters for stars, as quite recently demonstrated by discussions of several unnecessarily diverging sets of results.

In the following we shall review the present situation as regards model atmospheres and current methods for estimating fundamental parameters when using these models for stars of different types. The discussion of this broad topic must be very schematic, partly because of the lack of space, partly because of our lack of detailed experience from work on early-type stars. We shall try, however, to put the main emphasis on the development during the past three years.

3. SOME MORE DETAILED REMARKS ON STARS OF DIFFERENT TYPES

3.1. O-type stars

An important breakthrough for stellar-atmosphere modelling in general was the development of the complete linearization method by Auer and Mihalas in 1969. They also used their method to construct models of hot stellar atmospheres with a detailed non-LTE treatment of the H and He atoms, demonstrating the great improvement when compared with observations (cf., e.g., Auer and Mihalas, 1972).

In recent years, Kudritzki and collaborators, basically using the methods of Auer and Mihalas,have continued and developed this line of study in an impressive series of papers with detailed modelling of various types of hot stars (cf. Kudritzki, 1980, and references cited therein for a discussion of the methods of analysis). Thus, there are

series of analyses published on massive O stars (cf. Simon et al., 1983, for further references), on subluminous O stars (cf. Gruschinske et al., 1983, for further references) and of central stars in planetary nebulae (cf. Mendez et al., 1983, and references cited therein), as well as several analyses of more special objects.

Another very important contribution to the study of early-type stars in general is the grid of model atmospheres by Kurucz (1979). Although in LTE, these models are "blanketed", i.e. the effects of absorption lines have been taken into consideration by means of very extensive lists of data for atomic transitions, and by the so-called opacity-distribution-function (ODF) method. In the models of Kudritzki et al. only blanketing from hydrogen and helium is considered, and thus these two approaches are complementary.

For the formation of visual continua the LTE models seem valid as long as $T_{eff} < 30,000$ K (Kudritzki 1979). However, the structure of the outer layers of the models, the cores of the H and He lines and the formation of lines from many other species and some metal continua in the UV are also effected at much lower temperatures. For a $T_{eff} = 25000$ K main sequence star, the temperature differences in the surface layers may amount to several thousands of K between a non-LTE hydrogen-line blanketed model and a more fully blanketed LTE model, the latter being the cooler one. It is probable that real stars have temperature structures somewhere between these extremes, and it seems reasonable to assume that these differences could show up as lack of agreement between observed and calculated fluxes and spectra.

The non-LTE models with parameters chosen on the basis of spectral lines (see below) generally show good agreement with observed fluxes (cf., e.g. Kudritzki et al. 1983), except for the shortest wavelengths where the neglect of line-blocking becomes obvious in the comparison. For some stars, e.g. the OB subdwarf HD 149382 analysed by Baschek et al. (1982), the cores of the Balmer lines are reported to be deeper than the calculated ones, which is ascribed to the neglected blanketing. The Kurucz models are fairly successful in reproducing the observed fluxes of O stars (cf. Underhill 1982 and references cited therein). One exception is the infrared L and M bands where the Kurucz models are too faint as was pointed out by Castor and Simon (1983). The latter suggest that the flux deficiency of the models may be due to the LTE assumption - the temperature in the atmospheric surface layers would be expected to increase if the lines from the ions were treated in non-LTE, which would increase the infrared flux, although it is not clear that the observed excess of O⊤1 would result.

Castelli et al. (1980) and Remie and Lamers (1982) found that in the Kurucz models an extra UV blocking was needed in the ultraviolet (for $\lambda < 2000$ Å) in order to account for the observed fluxes of late O and early B supergiants and giants. They estimate that at least some fraction of the extra blocking needed (an increase by a factor of 1.5 to 2, according to Remie and Lamers, 1982) can be provided by increasing the microturbulence from 4 km/s to 10 km/s, which seems reasonable. Moreover, the opacity distribution functions of Kurucz are incomplete with respect to lines of higher metal ions.

The effective temperatures of O stars have been estimated from model atmospheres by using the integrated flux method (cf. Underhill et al., 1979, Underhill, 1982, Remie and Lamers, 1982, Heber et al., 1984), from flux gradients (e.g., Schönberner and Drilling, 1984) and from ionization equilibria of He (and H), calculated in non-LTE (Kudritzki and collaborators, cited above). The latter determine He abundance and the gravity (essentially from the Balmer-line profiles) simultaneously with T_{eff} stressing the importance of doing so in their analysis of ζ Pup (Kudritzki et al. 1983). This latter paper demonstrates that the previously claimed systematic differences between effective temperatures of O stars, derived from ionization equilibria, and those obtained from fluxes or angular diameters, may to a great extent be caused by inappropriate choices of surface gravity, small errors in reddening and underestimated errors in the integrated-flux method. Back-scattering of stellar photons by the far UV lines in the stellar wind, or other mechanisms that could heat the outer photospheric layers of O stars have earlier been advocated as explanations for the discrepancy between "photometric" and "spectroscopic" temperatures of O stars. The lack of correlation found by Underhill (1982) between spectral type and effective temperature, determined with the integrated-flux method, may demonstrate the importance of such phenomena.

Typical errors in T_{eff} and log g determinations for massive O stars, as quoted by Kudritzki and collaborators, are ± 2500 K and 0.15 dex, respectively. These uncertainties are intrinsic and basically a reflection of the uncertainties in the procedure whereby calculated H and He lines are fitted to observed ones. Systematic errors in the model atmospheres, such as the effects of the neglect of blanketing from ions, or of back-scattering from winds, are harder to estimate, but seem to be capable of leading to systematic errors of at least the same order of magnitude (cf. Husfeld et al. 1983). The effects of spherical extension and departures from hydrostatic equilibrium are generally thought to be small for the stars close to the main sequence or below it.

Relative errors in the effective temperatures, when derived with the integrated-flux method, are estimated to be within 5% (Underhill 1982, Remie and Lamers, 1982) but found to be considerably greater by Tobin (1983), especially for the hottest stars.

For the central stars of planetary nebulae the errors in the effective temperatures are greater. This is because the HeI lines are masked by nebular emission or because the stars are too hot to show these lines.

The relative errors in the He abundances derived by Kudritzki and collaborators for stars with a roughly solar helium abundance are typically given to be 10-20%, estimates again based on the internal errors in the fitting procedure. For helium in helium-poor stars, and for less abundant elements in general, the accuracy is less. E.g., in the detailed LTE analysis of the subdwarf HD 149382 Baschek et al. (1982) give what they suggest as rather optimistic error estimates, which, nevertheless, range from 0.2 dex (He) to 0.6 dex for the various chemical elements. Much of this error is ascribed to the uncertainty in the microturbulence parameter, which Baschek et al. consider to be the greatest source of error in their model analysis.

3.2. B-type stars

There are several studies showing that blanketed LTE models in the
grid of Kurucz (1979) are able to reproduce the visual fluxes and colors
of B stars in an accurate and consistent way. Recent examples of such
studies are the series of papers by Adelman and collaborators (cf. Adel-
man and Pyper 1983 and papers cited therein).   In this work spectro-
photometry was used to test the consistency between effective tempera-
tures obtained for B, A and F stars, using low-resolution scans in
direct comparison with models, or using measured and calculated colors
like the uvby system (synthesized by Relyea and Kurucz, 1978 and calcu-
lated directly from the scans). The internal consistency between these
different temperatures was good, as well as the agreement with direct
measurements of angular diameters and fluxes; the empirical temperature
scale of Code et al. (1976) was found to agree with the more theoretical
ones within approximately 5% in T_{eff}. Another example is the agreement
between two-color diagrams of the Geneva photometry with corresponding
model predictions (cf. Cramer , 1982) and of the theoretical calibration
of B-V and U-B versus T_{eff} of Buser and Kurucz (1978) with other cali-
brations (cf. Cramer, 1984). A comparison with predicted fluxes from
Kurucz's models in the vacuum ultraviolet with observations of late B
stars showed some discrepencies which were, however, considered by
Malagnini et al. (1983) to be "mostly instrumental effects".
     Lamers et al. (1983) find that for the B1 supergiant P Cyg, a con-
siderable amount of extra blocking is needed, as compared with the model
predictions, and they argue that this cannot solely be due to the stellar
wind but must be caused by mainly photospheric lines. Here, an enhanced
microturbulence might be reasonable to invoke. In contrast to this,
Castelli et al. (1980) found the observed UV blocking in stars later
than B5 to be smaller that predicted by the Kurucz models. However,
from comparisons between detailed synthetic spectra and high-resolution
IUE spectra of early B stars around 1200 Å Kamp (1982) concludes that the
Kurucz and Peytremann (1975) line list is seriously incomplete for hot
stars.
     There are other grids of models, less completely blanketed than
those of Kurucz, but still in use for B stars, such as the non-LTE
hydrogen-line blanketed models of Mihalas (1972b). In particular,
these models reproduce notably the cores of the Balmer lines quite well
(cf. the results for $H\alpha$, given by Heasley and Wolff, 1983). Yet, in
some cases an additional surface cooling, which would be provided by
ionic blanketing, can be traced in the line cores, cf., e.g., Heber
et al. (1984). For $H\alpha$ the wings are in better agreement with observa-
tions if calculated from the Kurucz models. The difficulties in re-
producing the red He I lines λ 5876 and λ 6678 in statistical-equilibrium
calculations (Heasley et al. 1982, using Mihalas's grid) might also be
diminished if blanketing were taken into acount more completely.
     Effective temperatures for B stars have been determined by model
atmospheres using the integrated-flux method, the Balmer discontinuity
(e.g., measured by the reddening-corrected uvby index c_1) or the ioniza-
tion equilibria, such as the SiII/SiIII/SiIV ratios. With unblanketed,
or only hydrogen-line-blanketed, models temperatures about 1000-2000 K

hotter result as compared with the Kurucz models, which is consistent with the first order difference between the temperature structures from the backwarming effect. Nowadays, the Kurucz models are generally prefered.

Underhill et al. (1979) derived effective temperatures using the integrated-flux method and the grid of Kurucz for a great number of B stars. These temperatures seem to agree rather well with those derived from the uvby photometry and the calibration of Relyea and Kurucz (1978). The calibration of Philip and Newell (1975), however, deviates systematically from this (Malagnini et al. 1983). For the early B stars a higher effective temperature was generally found from the Si lines than from the use of other methods. Recently, however, Erhorn et al. (1984) have argued that the consistent use of blanketed model atmospheres may make this difference vanish. In their study LTE was adopted; the non-LTE study of Si in B stars by Kamp (1976,78) suggests that this is acceptable for calculating ratios of equivalent widths and hence for estimating effective temperatures. We note in passing that the ionization equilibria of Si, Al II/ Al III, SII/SIII and CII/CIII in line blanketed LTE models lead to temperature determinations for the extreme He star BD +10°2179 which agree well with what is obtained from the flux distribution (Heber, 1983).

In conclusion, errors less than about 1000 K should be realistic at determinations of T_{eff} from model atmospheres for B stars, with known reddening. Significant systematic errors, however, may occur for the earliest B stars where the blanketing tends to be seriously underestimated by the Kurucz models, which could lead to overestimates of T_{eff}. For B-type supergiants, additional errors may occur due to uncertainties in the value of the microturbulence parameter.

The surface gravities of B stars are usually estimated from the Balmer line profiles. Recent examples of such measurements, calibrated by model-atmosphere calculations, are the studies of Hα in B stars by Heasley and Wolff (1983), the use of Hγ profiles by Adelman (1984) and of Hϵ in a study of halo OB stars by Keenan, Dufton and McKeith (1982).

Errors in the resulting log g values are generally estimated to be 0.1 - 0.2 dex when T_{eff} is given. However, a systematic study (using different hydrogen lines) of possible errors in these determinations would be valuable, not only in view of the inconsistency of 0.25 dex traced by Lennon and Dufton (1983) between gravity estimates from the Hϵ profiles and those from Hγ and β indices for stars in NGC 6231.

The problem of determining accurate abundances for B stars is a complicated one, due to the relatively small number of suitable spectral lines, the uncertain microturbulence parameter and departures from LTE. Studies of such departures - for He I (Auer and Mihalas 1973a, Heasley and Wolff 1982), for Be II (references given in Boesgaard et al. 1982), for OI (Baschek et al. 1977), for Ne I (Auer and Mihalas, 1973b), for Mg II (Mihalas 1972a), CaII (Mihalas 1973) and for SiII,III and IV (Kamp 1976,1978) have demonstrated that the effects may well be considerable. However, not all odd spectral line strengths in B stars, such as CaII λ 4267, are easily explained as the result of departures from LTE (cf. the non-LTE calculations of Lennon, 1983).

Errors of ± 0.2 dex or less are often quoted in abundance analyses of B stars. The systematically non-solar results obtained for some elements (e.g., the underabundance of carbon) cast some doubts on our understanding of the systematic errors involved. Some of the stellar-solar differences may, however, be due to errors in the oscillator strengths, since one often cannot use the same lines for B stars and the Sun. One should try to bridge the gap by a two-step differential analysis, with an early F-type dwarf as an intermediate point, as has been suggested by, e.g., Adelman (1984).

3.3. A-type stars

For A stars, as well, the comparisons between observed fluxes and those of the LTE models of Kurucz (1979) show satisfactory over-all agreement, in the visual and with certain exceptions also in the ultra-violet (Böhm-Vitense 1981b and 1982, Kurucz 1980, Malagnini et al. 1982, Adelman et al. 1980, Adelman and Pyper 1983). However, over-ionization of carbon and silicon was found in the non-LTE calculations of Snijders (1977a and b) and this leads to observable effects for the UV continua of late B and early A stars at $\lambda < 1200$ Å. The temperature sensitive intensity jump at 1600 Å has been studied by Böhm-Vitense (1982) and used by her for deriving effective temperatures for A and F stars. Since there are some discrepancies between calculated and observed fluxes in the wavelength region between 1700 and 1800 Å, she chose the flux ratio F_λ (1900 Å)/ F_λ (1420 Å) as a suitable temperature measure. She found, however, that the calculated flux at 1900 Å had to be lowered by 0.1 dex for $T_{eff} < 9000$ K in order to agree with temperatures derived from the F_V/F_λ (1900 Å) ratio, when F_V is the flux in the visual V band.

It seems possible to determine the effective temperature of an early A dwarf from a well observed absolute flux distribution with an accuracy of about ± 200 K, as is illustrated for the Vega and Sirius cases (cf. Dreiling and Bell, 1980 and Bell and Dreiling, 1982, Selby et al. 1983) and about the same accuracy seems achievable for later type A stars, e.g. using the semi-empirical calibration of 1600 Å jump (Böhm-Vitense, 1982). For the giants and especially the supergiants the fit to the Kurucz models is less satisfactory and the uncertainties in T_{eff} are considerably greater. Note, however, the quite consistent T_{eff} and log g results from different methods that Desikachary and Hearnshaw (1982) obtain for Canopus (F0 Ib-II) on the basis of Kurucz models and near UV-visual-infrared observations. The gravities are generally derived from Balmer-line profiles, and accuracies of about ± 0.2 dex may be expected (Dreiling and Bell, 1980, Adelman et al., 1984).

The abundance determinations, even for the brightest early A stars, are difficult and uncertain, as a result of the small number of suitable spectral lines. E.g., iron in Vega appears underabundant by 0.5 ± 0.3 dex (Dreiling and Bell, 1980), which may at least partly be a non-LTE effect. The errors in the CNO element abundances of Vega and Sirius are considered somewhat smaller (± 0.2 dex or less, Lambert et al. 1982). Much of the interest in abundance determinations for A stars has, for natural reasons, been directed towards the study of Ap and Am stars. Although the wealth of sharp metal lines in these spectra simplifies an

abundance analysis, there are several complicating circumstances which
should be borne in mind. One is the fact that the metal-line blocking
in the ultraviolet is different (cf. Böhm-Vilense 1981b) and this should
be considered in the model atmospheres. Muthsam (1979) has calculated
a grid of line-blanketed models for Ap stars and used these for modelling
specific stars (Muthsam and Stepién 1980, and references listed therein).
Other groups have used the over-all metal-enhanced models of Kurucz
(1979).

Other interesting complications are the observed inhomogeneous distri-
bution of the elements across the surface of the star, and the expected
non-uniform distribution with atmospheric depth (cf. Alecian, 1982).

3.4. F-type stars and solar-type dwarfs

It was pointed out by Böhm-Vitense (1970) that theoretical U-B, B-V
colors for F dwarfs did not agree with the observed two-color diagram.
Kurucz's (1979) models are also not quite successful in this respect
(Buser and Kurucz 1978, Böhm-Vitense 1981b), nor do they reproduce the
observed uvby colors with the precision desired for many applications
(Relyea and Kurucz, 1978). The use of a modified mixing-length theory
of convection diminishes some of these discrepancies (Lester et al. 1982,
Buser and Kurucz 1985) but does not solve all problems. Scanner obser-
vations (Böhm-Vitense, 1978) tend to show a flux deficiency around 4100 Å
for stars with B-V > 0.25, as compared with radiative equilibrium models.
It was suggested by Nelson (1980) that this phenomenon is caused by
temperature (and thus opacity) inhomogeneities, generated by convective
overshoot. According to Nelson's estimate the existence of inhomogenei-
ties should reduce the flux around $0.4\,\mu$ by $0^{m}\!1$ or so, but the effect
was expected to be smaller for the late F stars. This estimate is,
however, very schematic and more detailed simulations of convection in
F stars are needed before any firm conclusions may be drawn.

The problems for the early F type star models may, or may not, be
related to those of the Sun. There is still some uncertainty as regards
which solar photospheric model is the most realistic one, although many
investigations suggest that the semi-empirical Holweger-Müller (HM)
(1974) model is most successful in reproducing continuum fluxes and
lines (Lambert 1978, Holweger 1979, Gehren 1981). Sauval et al. (1984)
find a very impressive consistence between observed and calculated pure
rotation lines of OH when the Holweger-Müller model is used. However,
Rutten and Kostik (1982) have argued that the success of the HM model
would not be so impressive for the iron lines, if departures from LTE
had been taken into consideration properly, and these authors instead
favor models with greater temperature gradients.

The theoretical solar models, although not very far from the
Holweger-Müller model, do not reproduce the observed solar fluxes in
the blue and ultra-violet very well. E.g., the Kurucz (1979) model is
too blue (B-V = 0.60), as is the modified one after the introduction of
the alternative mixing-length formulation (Lester et al. 1982), and they
seem to have too little blocking in the ultraviolet, which is certainly
also the case for the model with solar parameters in the grid of Bell et
al. (1976), cf. Gustafsson and Bell (1979). On the other hand, at least

the latter model is too cool by about 150 K - if the extra blocking
required in the uv is introduced this temperature discrepancy vanishes
due to the back-warming effect.

Gehren (1981) found that the effective temperature calibration of
B-V and of the Strömgren b-y color, based on Kurucz's models did not
agree with that from Hα and Hβ profiles. The same is true for the b-y
colors calculated from models by Bell and Gustafsson (cited by Nissen
and Gustafsson, 1978). Gehren suggests an explanation of this discre-
pancy in terms of missing line opacity in the calculations, although
other possibilities are also mentioned.

Magain (1983)showed that the assumption that the discrepancy be-
tween the observed and calculated solar flux in the violet and near
ultraviolet is due to a veil of very weak neutral metal absorption lines
of rather high excitation would reproduce the observed temperature sen-
sitivity, and the metal abundance sensitivity for the blue-violet-ultra-
violet colors of the UBV and Geneva systems. These results were based
on blanketed theoretical model atmospheres for solar-type stars, calcu-
lated with the program described by Gustafsson et al. (1975). The si-
tuation is, however, still unclear and definite conclusions must await
detailed simulations of convective overshoot (such as those Nordlund
1978,1982,1984 has made for the Sun) for stars of different T_{eff}, $\log g$
and $[M/H]$,and further studies of veiling of weak spectral lines.

The Balmer discontinuity index of the uvby system, c_1, is an ex-
cellent gravity measure for F-type stars, but in view of the problems
discussed above one should use theoretical calibrations of it with some
care, and prefer more empirical calibrations (such as that of Crawford
1975, and Nissen and Gustafsson 1978). In particular, the metal-
abundance sensitivity of the index is still not well known. Similar
remarks are valid for the calibration of the abundance criterion m_1
(cf. Olsen, 1982) for which the empirical calibration of Nissen (1981)
should be preferred.

Abundance determination is also affected by the problems discussed
above; e.g. an uncertainty in effective temperature for a star of 200 K
may well correspond to a metal-abundance error of 0.1 - 0.2 dex. A
complicating circumstance is the problem with the solar colors; in
any differential abundance analysis relative to the Sun where the effec-
tive temperature of the star is estimated from a color index, one needs
to know the corresponding solar color. There still seems to be an
uncertainty of at least ±0.03 in $(B-V)_\odot$ and similar uncertainties in
other colors, corresponding to about ±75 K in T_{eff} for solar-type stars.

Another problem in abundance studies, for F- and G-type stars, is the
non-LTE effects. The available statistical-equilibrium calculations for
atoms and molecules in late-type stars in general are as yet quite un-
certain, due to uncertainties in ultraviolet fluxes (of vital impor-
tance for photoionization) and in collision cross-sections and possibly
too over-simplified model atoms. The recent calculations of Saxner
(1984) suggest that iron is significantly overionized in the F star
atmospheres, and that this effect is metal-abundance sensitive, since
the more metal-poor stars let more photoionizing uv flux through. The
resulting iron abundances determined from weak lines are predicted to be
underestimated by up to a factor of two for the hottest Intermediate

Population II dwarfs. The second order effects on the model atmospheres are also found to be important.

One should finally keep in mind that the fundamental model assumption as regards plane-parallel stratification may cause errors in abundances of at least 0.1 dex (cf. Hermsen 1982).

3.5. G-K giants

The models in widest use for analyses of yellow-orange giants are the blanketed models of Bell et al. (1976), cf. also Gustafsson et al. (1975). They include blanketing from CN, C_2, CO and other molecules, as well as atomic lines. These models have been confronted with observations in various ways. E.g., the fluxes and colors were compared with observed spectra, scans and colors by Gustafsson and Bell (1979) and a good agreement was found except for the ultraviolet blocking in the models which was too small, leading to too bright uv magnitudes by up to $0^m.4$. This discrepancy was tentatively ascribed to a veil of very weak metal lines, not included in the line list of the models, the inclusion of which would not change the structure of the models significantly. With the recent "hotter" temperature scales for red giants (see below), a similar veil also needs to be invoked in the violet spectral region (cf. Frisk et al. 1982) and its structural effects become somewhat more important. Another discrepancy appeared in the CN band color indices, but that is because solar [N/Fe] ratios were adopted in most models (cf. Gustafsson and Bell 1979, Lambert and Ries 1981 and Kjaergaard et al. 1982).

Attempts to test the models by comparison between predicted and observed profiles of strong lines also resulted in a reasonable agreement but with not fully conclusive results as regards deviations from the predicted structure of the upper layers (cf. Gustafsson 1980 for references).

The effective temperatures of red giants have been estimated by the integrated flux method, from colors and from studies of excitation equilibria. In addition one should mention the lunar-occultation diameters of Ridgway et al. (1980, 1982a) where the use of model atmospheres is confined to corrections for limb-darkening. We note in passing that the observed limb-darkening as a function of wavelength of α Tau (K5 III) by Ridgway et al. (1982b) gives some checks on the model atmosphere calculations and, within the yet considerable error margin agrees with the predicted one.

The temperature scales based on colors and model atmospheres have recently been revised upwards by almost 200 K, relative to earlier ones such as that of Bell and Gustafsson (1978, cf. also Kjaergaard et al. 1982). This is partly due to the choice of a greater solar color index and the recent use of more well-defined photometric systems like that of Wing (1971) calibrated for G-K giants by Wing et al. (1985), and that of Frisk et al. (1982) and Frisk and Bell (1985). A consequence of this is that the predicted blue color indices are too small and the assumption of a previously unconsidered veil of weak spectral lines in the uv must be extended into longer wavelengths. The temperature for Arcturus of Frisk et al. (1982) is in very good agreement with that

of Blackwell and Shallis (1977), derived with the infrared flux method.

High effective temperatures were also derived by Lambert and Ries (1981) from excitation equilibria of neutral iron - however, in view of probable departures from LTE (see below) this scale must be regarded as rather uncertain.

The gravity determinations for G-K giants is still a matter of some controversy (cf. the discussion of Arcturus by Trimble and Bell 1981). The methods available include the use of ionization equilibria, of the wings of pressure-broadened spectral lines and of lines of pressure-sensitive molecules, such as MgH; in fact a fourth method, based on the different pressure sensitivity of the H^--opacity relative to that of the HI scattering is exploited in certain photometric systems, see Gustafsson and Bell (1978). These methods are subject to uncertainties of different importance, and they have been intercompared for the test case of Arcturus in a recent study by Bell et al. (1984). The resulting logarithmic gravities range from 1.4 to 1.8 (cgs units), and it is concluded that the method of Blackwell and Willis (1977), based on pressure-broadened lines, should be preferred, especially for stars with greater gravities than Arcturus, i.e., for most G and K giants and subgiants.

The problems of determining abundances for late-type giants have recently been reviewed several times (Gustafsson 1980,83, Taylor 1983), and here we shall only consider them briefly. The possible errors in T_{eff} and $\log g$ may cause considerable problems, especially for estimating abundances of elements such as nitrogen, where the determination is dependent on the molecular equilibrium (cf. Kjaergaard et al. 1982). The model structure uncertainties may be important, especially for strong lines and low excitation lines (Gustafsson 1983). Departures from LTE have been traced empirically in some cases (cf., e.g., Ruland et al. 1980, Brown, Tomkin and Lambert 1983, Steenbock 1983, possibly Kovacs 1983 and Luck and Bond 1983). Unfortunately, one could hardly assume that any elemental abundance for any giant is much better determined than to 0.2 dex, although the internal consistency between different weak lines as measured with modern equipment sometimes suggests a considerably smaller error. The systematic errors may in some cases be significantly greater and, worst of all, it is hard to say when.

In a series of papers Luck has analysed G and K supergiants (cf. Luck 1982a and references cited therein), using models calculated with the program of Gustafsson et al. (1975). He derives effective temperatures and gravities from Fe excitation and ionization equilibria, respectively, and finds a temperature scale which is about 200 K hotter at a given B-V than that of Bell and Gustafsson (1978). It seems natural to ascribe this discrepancy to the veil discussed above, which was not considered in the model fluxes, and to the zero point of colors of the model calibration, even though departures from the Boltzmann excitation equilibrium may also be of importance. Luck also finds his gravity determinations to agree well with estimates from evolutionary tracks, and estimates errors in $\log g$ of, at the most, ± 0.3 dex. He gives typical errors in the resulting abundances of $\pm 0.2 - 0.3$ dex, but admits that there may be additional systematic errors.

3.6. M giants and supergiants

At least two grids of model atmospheres for M giants and supergiants have been published – that of Tsuji (1978), where blanketing from a number of molecules including TiO and H_2O was taken into account using some rather crude approximations, such as the so-called Voigt-analog – Elsässer band model, and the grid of Johnson et al. (1980) where the more detailed Opacity-Sampling method was used. The models of the latter grid seem to agree quite well with those of Tsuji and also, for temperatures above 4000 K where TiO is not very important, with those of Bell et al (1976). Tsuji (1978) showed that his models agreed well with observed spectral distributions of M giants, and he applied the integrated-flux method to establish an effective-temperature scale for M giants. He estimated that the temperatures are accurate to within ±150 (4%,Tsuji 1981a). This scale agrees nicely with that of Ridgway et al. (1980), based on lunar occultation data. Piccirillo et al. (1981) also found a good agreement between the Ridgway et al. scale and that from the models of Johnson et al. (1980), when used for calibrating the Wing eight-color photometry. The temperature of Betelguese (M2 Ib), derived with the infrared flux method by Tsuji (1981a), T_{eff} = 3800 K, agrees well with that estimated from the excitation equilibria of CO (Lambert et al. 1984) but is significantly greater than the interferometric value of Balega et al.(1982).

The problem of determining the surface gravity for M stars spectroscopically is a very difficult one; due to the lack of unblended ion lines, ionization equilibria cannot be used, while the continuum drawing problems make damping wings of pressure broadened lines difficult to trace. The profound effect of the molecular-line blanketing from TiO was nicely demonstrated by Piccirillo et al. (1981). Attempts to use hydride lines and lines from the corresponding neutral metal atom could be attempted but will require very good temperature estimates.

The placement of the continuum is also a major problem for abundance determinations in M stars from lines in the visual and near infrared. In their analysis of Li and Al in M giants and supergiants Luck and Lambert (1982) estimate that these difficulties lead to an error of 0.2 dex in the Li abundance determination. They find that non–LTE effects should be small and estimate their total errors at ±0.3 dex. Luck (1982b) finds uncertainties of ±0.4 dex in his chemical analysis of two M stars, again referring to the continuum location problems as the major source of error. The analysis of Lambert et al. (1984) of CNO abundances in Betelguese is more satisfactory from this point of view, since it is based on high-resolution spectra beyond 1.5 microns, where the blending problems are less severe. Also, this analysis uses the vibration-rotation bands of CO, NH and OH (in addition to the electronic CN red system) where the departures from LTE are thought to be of less importance.

Departures from LTE in early M stars have been suggested as occuring in the ionization of Ca by Ramsey (1977, 1981). However, it seems reasonable to assume that the empirical support for this may instead be effects of difficulties in locating the continuum (Luck 1982b).

Evidence for inhomogeneities in Betelguese was reported by Goldberg et al. (1982) and by Hayes (1980, 1984)and further discussed by

Goldberg (1984). It is not known what errors these inhomogeneities
introduce into the abundance estimates. The effects of spherical ex-
tension should be of importance for M giants and supergiants, as demon-
strated by Watanabe and Kodaira (1978, 1979) and Schmid-Burgk et al.
(1981). In fact, the formation of molecules amplifies these extension
effects further, such that they are greater than first order estimates
tend to show, and also depend on the chemical composition in a com-
plicated way. However, the extension d ($\propto (g_{surface}R)^{-1}$) can in prin-
ciple be determined from stellar spectra, and this opens up the pos-
sibility of determining the stellar radius, in addition to surface gra-
vity and effective temperature. Thus, stellar masses for single stars
should in principle be possible to determine spectroscopically for ex-
tended stars. The practical possibilities for doing this have been
discussed by Scholz and Wehrse (1982).

3.7. Carbon stars

    For the hotter carbon stars, the R stars, two grids of models with
detailed blanketing have been calculated - one by Olander (1981) using
the program of Gustafsson et al. (1975) and one by Johnson and O'Brien
(cited by Dominy, 1984). The models of the two grids have been inter-
compared by Yorka (1981), who found them to agree well, which is of in-
terest since the methods for handling the heavy blanketing are different
(based on the ODF and OS technique, respectively), and since the molecu-
lar line lists are based on different compilations of data. A valuable
review on model atmospheres for late-type stars has been published by
Carbon (1979).
    There is, as yet, no systematic comparison between predicted fluxes
of these models and observations. However, comparisons like that of
Dominy (1984, his Fig. 1) suggest a reasonable agreement between compu-
ted and calculated fluxes. Also, there is no fundamental theoretical
calibration of T_{eff} versus colors yet available - in his analysis
Dominy (1984) had to rely on the corresponding relation for the G-K
stars. It should be noted that the version of the integrated flux method
used by Tsuji (1981a and b) for cooler stars, where the flux in the L
band at 3.5 μm is compared with the integrated flux, cannot be used, due
to the characteristic excess of flux of R stars in the L band. In all,
errors of several hundreds of K are to be expected in the current esti-
mates of temperatures for R stars.
    As regards the gravities the situation is very difficult. The heavy
blending and continuum location problems make measured equivalent widths
of the few ionic lines highly uncertain and profiles of pressure-broadened
lines difficult to measure. The molecular equilibria are hard to use
since the chemical composition is unknown and has to be determined from
the same data.
    The uncertainties in model parameters and in the continuum location
make the results from abundance analysis of R stars uncertain. In his
pioneering study Dominy (1984) suggests errors in the interval 0.3-0.6
dex, or even more for the N abundances when estimated from the CN lines,
since the propagation of errors in C and O abundances and the gravity
uncertainty makes the situation particularily difficult.

For the cooler carbon stars (of spectral type N) grids of models have been calculated by Querci, Querci and Tsuji (1974), Querci and Querci (1975), by Johnson (1982) and by Eriksson et al. (1984b). Querci and Querci (1976) have compared spectra and colors of their models with observations, with rather inconclusive results, partly because the role of grain opacities is not well known.

A worrying discrepancy between the carbon-star models and the real stars was the fact that the hydrogen quadrupole lines at 2.1 μm were predicted to be strong by the models but not seen in the spectra (Goorvitch et al. 1980). Although H_2 lines were later detected in N-type FTS spectra (Johnson et al. 1983), they were found to be considerably weaker than predicted from the models. A similar problem exists for the H_2 lines in M giants (Tsuji 1983).

The models of Querci et al. and of Johnson do not contain any absorption from polyatomic molecules. Eriksson et al. (1984a) included preliminary opacity estimates by Jørgensen (1982) for HCN and later C_2H_2 and found drastic effects - the pressure at a given optical depth for stars with T_{eff}=2500 K could decrease by two orders of magnitude as a result of the new opacity. Therefore, the H_2 density decreased considerably and we conclude that the formation of polyatomic molecules may be an explanation for the weak H_2 lines in carbon star spectra. This conclusion should, however, be taken as preliminary until current ab initio calculations of HCN, C_3 and C_2H_2 have been pursued (Jørgensen et al. 1984). There is the alternative possibility that the outer photospheres of N stars are heated by non-thermal processes, which would diminish both the polyatomic opacities and the H_2 number densities (cf. Johnson et al. 1983 and Goebel et al. 1983). Another possibility would be that the carbon stars may be hydrogen poor, which would explain the apparently missing "H^- peak" around 1.6 μm in their spectra (Alexander et al. 1984).

The temperature scale for carbon stars established by Tsuji (1981b), using the integrated-flux method and the Querci et al. grid, must for obvious reasons be considered as preliminary. However, we have recently derived effective temperatures for N stars by using infrared colors, compared with theoretical ones,for models with C_2H_2 and HCN included. We find an agreement within 200 K with Tsuji's scale, which is satisfactory. Tsuji's scale is also consistent with the few angular diameter measurements available for carbon stars.

A major problem for N stars is the derivation of surface gravities from spectra. It is not clear whether this problem can be solved at all with any acceptable errors. It will at least require very reliable T-P structures (which requires good estimates of polyatomic opacities) and very good synthetic spectra around the spectral features to be used. Determinations of CNO abundances, over-all metal abundances and abundance ratios are nevertheless within reach for these stars, when based on lines in the infrared. However, one should note that an acceptable abundance determination requires an iterative procedure when determining the fundamental parameters, since the structure of the model atmosphere is very dependent on the chemical composition as a consequence of the heavy blocking. The resulting errors are expected to be considerable.

A recent example of an analysis of an SC-type star is the study of
UY Cen by Catchpole (1982). Here, the resulting typical errors in the
abundances are estimated to ±0.5 dex. The problems of the pure S stars
are somewhat special (and not yet fully explored) due to the delicate
molecular equilibrium and effects of blanketing from other molecules
than those of importance in M and C stars.

For the cooler carbon stars the formation of dust grains may cause
major problems, since the calculation of their concentration and their
heavy opacity probably cannot be made within the framework of a steady
state model (cf. Woodrow and Auman 1982).

3.8. Late-type dwarfs

For the K dwarf atmospheres, usually scaled solar models or model
atmospheres from the metal-line-blanketed grid of Peytremann (1970) or
from that of Eriksson et al. (1980) are used. (The latter grid, which
is consistent with that of Bell et al. 1976, and thus also includes the
blanketing from molecular lines, is unpublished but available on request.)
Steenbock and Holweger (1981) report indications from the Mg b-line
profiles of ε Eri and 40 Eri A (K2 V and K1 V, respectively) that theo-
retical models seem to be too cool in the upper photosphere. These
authors find that scaled HM solar models give better fits.

Effective temperatures for the K dwarfs are usually obtained from
the near-infrared colors, but no well-established temperature scale
based on the model-atmospheres for these stars has yet been published.
The gravities may be derived from bolometric fluxes (parallaxes are
often well-known) and temperatures, if the mass is estimated from the
luminosity. Alternatively, ionization equilibria, pressure-broadened
lines or molecular lines (e.g., from hydrides) may be used for this
purpose. Attempts to compare the methods and their resulting gravities
have as yet not been fully conclusive (cf. Perrin 1983); earlier reports
on significant inconsistencies between the ionization equilibrium gravi-
ties and those derived from parallaxes are not valid (Perrin et al. 1975,
Hearnshaw 1976b), except for possibly for metal-deficient dwarfs (Hearn-
shaw 1976a).

Typical errors claimed in abundance determinations relative to the
Sun for K dwarfs seem to be ± 0.2 dex, which may be somewhat optimistic
in view of the uncertainties in models and in the temperature scale, at
least for the late K dwarfs. In their spectra it may also be difficult
to locate a true continuum.

For M dwarfs, Mould (1976a) in his pioneering work calculated a grid
of model atmospheres with blanketing from atoms and molecules (in parti-
cular from H_2O and TiO) taken into account, using a rough ODF method and
a smeared line model for the molecular opacities. He applied these
models in further studies of M dwarfs (Mould 1976b and references cited
therein, see also Hartmann and Anderson 1976) and, to our knowledge,
this work still belongs to the most advanced photospheric analyses for
M dwarfs. The full arsenal of detailed blanketed models and synthetic
spectra should be used in future work for analysing the high-quality
spectroscopic material that may be obtained today for these stars.

4. CONCLUSIONS

The superficial review in the previous section may have given the impression that, although there are still some questions of debate left, and some corners in the HR diagram which have not been fully explored with the methods of detailed quantitative spectral analysis, the general success of physical modelling is remarkable. This is partly an illusion, however. It is interesting that most of the cases under intensive debate in this field of research, such as the effective temperature scale of O stars, the temperature scale of F stars, the nature of the so-called super-metal-rich stars (Taylor 1983, and references cited therein), the gravity of Arcturus, the metal abundance of the metal-rich globular clusters (Gustafsson 1982, Bessell 1983, Cohen 1983, D'Odorico et al. 1984), the effective temperature of Betelgeuse, etc., have one characteristic in common: several different methods have been attempted and they tend to give different results. In many other cases, where the errors in the fundamental parameters are thought to be rather small, different or independent methods have not yet been tried. Admittedly, many or most of the conflicting results in the cases listed above may be due to trivial errors in the observations or in the analysis. But some of the discrepancies may reveal more fundamental errors in the models or even in our basic ideas of how stellar atmospheres are structured. This possibility, and the good reasons discussed above in Sec. 1 for improving the parameter determinations further, makes it worthwhile to proceed in attempts to fundamentally improve the models. A third important reason for doing so is the lack of theoretical self-consistency in contemporary model atmospheres.

The future modelling of stellar atmospheres requires more profound theoretical studies of various aspects and detailed numerical simulations of different processes in the atmospheres. This includes investigations of convection and its consequences, of mass flows, of non-thermal heating, of effects of inhomogeneities, of departures from LTE and of grain-formation. It is also important to consider the interplay between these different non-classical aspects of stellar atmospheres since they affect each other in several important ways. Theoretical efforts must be combined with systematic observational studies of direct and indirect diagnostics of the phenomena, e.g., of spectral line shifts and asymmetries, of spectra at different wavelengths in order to disclose the somewhat symbiotic character of spectra from inhomogeneous atmospheres, of suspected departures from LTE in spectral lines, and of thermal emission from dust as compared with temperature diagnostics for the outer photosphere.

The more fundamental studies should be combined with systematic attempts to develop more empirical model atmospheres, at least for a number of "standard stars", based on obtainable and suitable data such as the observations of vibration-rotation lines of different strengths and of different molecules, wing profiles of strong spectral lines and continuum fluxes. This should be supplemented with large scale synthetic-spectrum calculations and comparisons in detail with high signal-to-noise spectra, covering extensive spectral regions for these stars, in order to improve the calibration of low-resolution criteria for fainter stars.

It does not seem possible to achieve any significant improvement in the accuracy of determinations of stellar parameters from model atmosphere comparisons that one can obtain today unless at least part of the program sketched above is realized. This program will require very ambitious collaborative efforts between theorists and observers; and also the use of different methods and an interest in studying why these different methods sometimes give conflicting results. Conflicts should not be swept under the rug, nor should they force us into definitive positions; scientific progress is a dialectic process. In return we shall learn much more about "the stars that are up there".

ACKNOWLEDGEMENTS

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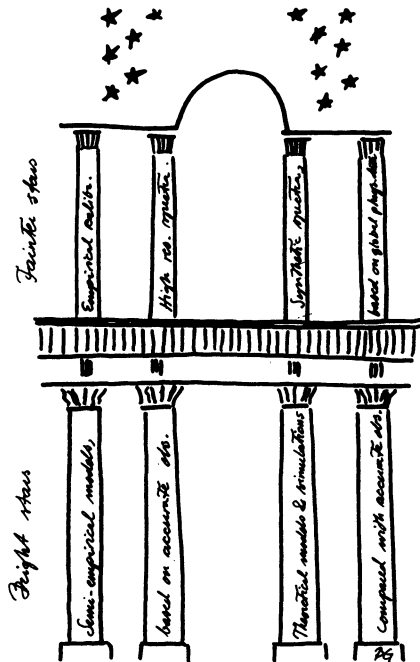
Steps towards improved stellar fundamental parameters from model atmosphere analysis – a subjective interpretation of the architecture of the great meeting room at Villa Olmo, Como.

DISCUSSION

GUSTAFSSON: I would like you to look upwards and consider the nice paint-
ing by Dominico Pozzi on the ceiling of this beautiful room. The paint-
ing could be called: "Il dilemma delle calibrazioni di astrofisiche",
and if you translate that, with some Underhillian sharpening, you may
call it the "horrible problem of astrophysical calibration". You see
three groups of people and also, with some difficulty you may find stars
and two stellar constellations. There are two groups of people in the
sky, the photometrists and the spectroscopists, and they seem to be
interested, to some extent, in the stars. They are not debating very
much, however. And then, on the ground, we have the theorists. They
are in intensive debate, but they don't even look at the stars. I think
that the point the painter wants to make is that, in order to improve,
we have to collaborate more. More interaction, more discussions, even
more conflicts. After all, scientific progress is a dialectic process.

ROSSI: Concerning the empirical temperature calibration for late-type stars, I have to make a warning about the fact that when analyzing the 2.2 micron sky survey and the AFCR2 catalogues, you see IR excesses for K-type stars. I wish to make a remark about the atmospheres of C stars. I am very interested in your models for C stars. In these stars grain formation in the atmosphere is very likely and one has to take it into account.

GUSTAFSSON: I wonder if IR excesses for "normal" K giants are important even in the near IR? Grain formation in carbon star atmospheres is really problematic; at least for effective temperatures < 2500 K. The models predict temperatures cold enough for graphite and SiC grains to form in the outer layers. Probably, this extra important opacity cannot be treated within the framework of static models and possibly not even with models with stationary flows.

PETERS: I was delighted to hear your cautionary remarks concerning the use of the microturbulence parameter in the analysis of stellar spectra. For the early B stars, the meaning of this parameter is not entirely clear. It could be a real microturbulence, a non-LTE coverup, a reflection of an incorrect T-tau relationship in the atmosphere, etc. A curious result still prevails that the deduced microturbulence parameter for early B stars increases with increasing effective temperature and decreasing log g.

Temperatures for early B stars deduced from the continuous energy distribution observed in the region longward of the near ultraviolet are indeed strongly dependent on the assumed reddening correction because we are observing only the Rayleigh-Jeans part of the distribution. The situation is improved if we use flux data in the far UV to the Lyman limit where these stars radiate most of their energy. Recent Voyager UVS continuum observations of such stars from 900 - 1700 Å, which are being analyzed by Ron Polidan and myself, promise to be especially valuable for obtaining the temperatures of B stars and I refer you to our paper in this symposium volume for further details.