THE POSSIBILITIES OF SYNTHETIC PHOTOMETRY

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ABSTRACT. The use of calculated colour indices, based on model stellar atmospheres, is discussed. It is concluded that such synthetic photometry has a variety of interesting applications, well worth further exploration and systematic utilization.

1. INTRODUCTION

The possibilities in the art of calculating stellar spectra and colours seem so promising that one astronomer asked some years ago: "Why should we observe stellar colours when we could more easily calculate them?" One answer to this question would be that although the calculations reproduce most observed two-colour diagrams they are still not in perfect quantitative agreement with the observations, thus indicating that there is more to learn about the real stars. Here, I shall first sketch the present agreement, and lack of agreement, between calculated and observed stellar colours for different types of stars. After that I shall comment on the use and the potential of synthetic colours. The space available does not admit any comprehensive discussion - the reader is advised to consult more extensive review papers such as Gustafsson (1979) and Gustafsson and Jørgensen (1985) and the original literature. In the following references will mainly be made to recent work, but also frequently to Gustafsson and Bell (1979, Paper I).

2. TESTING THE PROPERTIES OF MODEL ATMOSPHERES

Several studies have shown that the agreement between calculated fluxes for models from the grid of Kurucz (1979) and observed fluxes and colours is impressive and satisfactory for most applications for A and B stars. Some recent studies where this is noted are Adelman and Pyper (1983) and Adelman (1984), Cramer (1982, 1984a and b), Glushneva (1983 and 1984, and references cited therein), Holberg, Forrester and Shemansky (1982), Lanz (1984), Malagnini et al. (1982 and 1985), and Dobias and Plavec (1985). A fair agreement is also found for chemically peculiar stars, such as Ap and Am stars, if the relevant abundance peculiarities are taken into account in the models and the

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spectra (see, e.g., Muthsham and Cowley, 1984, and Lane and Lester, 1984). There are, however, some problems noted for O stars (normally referred to departures from LTE; cf., e.g., Kudritzki et al. 1983) and for supergiants (non-LTE?, missing uv lines?, velocity fields?, cf., e.g., Remie and Lamers, 1982, and Lamers, de Groot and Cassatella, 1983).

For F- and G-type stars the discrepancies are disturbing - the calculated UBV and uvby colour-colour diagrams do not fit so well (Buser and Kurucz 1978, Relyea and Kurucz 1978), and these discrepancies have been referred to errors in the standard mixing-length convection recipe (cf. Lester et al. 1982) and to inhomogeneities (Nelson 1980, Böhm-Vitense, 1982). It should be noted, however, that Bell and Oke (1985) and Bell (1986) report a very satisfactory agreement between model fluxes and colours and observations of Pop. II dwarfs (cf., however, also Magain 1984, 1985) - for these stars effects of convection should be visible due to the transparency of the atmospheres while errors due to missing faint metal lines in the models are expected to be of less importance.

The recent temperature calibration by Saxner and Hammarbäck (1985), based on the IR-flux method, for F-type dwarfs indicates that at least the calculated b-y colours are realistic for these stars. At shorter wavelengths, however, the wellknown "missing-ultraviolet-opacity problem" occurs - this was found to increase with increasing metal abundance for G and K giants in Paper I, and strong arguments for its origin as the result of the effects of a veil of metal lines, not included in the line lists, were given by Magain (1983), Buser and Kurucz (1985) and Kurucz (1986). A study of Arcturus by Frisk et al. (1982) suggested that this problem may be of importance also in the violet and blue spectral regions for K-type stars - this conclusion is, however, dependent on the effective temperature of Arcturus which is still uncertain. A similar tendency for more metal-poor red giants was possibly traced by Luck and Bond (1981, 1985), see also Bessell and Norris (1984). In the infrared spectral region the agreement between observed and calculated colours for G and K stars seems quite satisfactory, according to recent work by Bell and Gustafsson (1986).

The results for cooler stars are still rather scanty. An impressive early work was the study of Betelgeuse (M1-M2 Iab) by Tsuji (1976, 1978) who showed that a good fit to the observed fluxes would result, provided that the star was carbon poor and nitrogen rich, relative to the Sun - a condition which has subsequently been confirmed spectroscopically (Lambert et al. 1984). Steiman-Cameron and Johnson (cited by Johnson 1986) report a rather good agreement between calculated and observed VRIJKL and Wing narrow-band photometry for early M stars (cf. also Piccirillo, Bernat and Johnson, 1981) while problems seem to exist for cooler M stars and in the ultraviolet. No systematic comparison between observed and calculated colours for R-type stars is known to the present author, although adequate grids of models now exist for these stars (Olander, 1981, Yorka and Johnson, 1986). Comparisons between observed and calculated fluxes for N-type stars show a good overall agreement but the polyatomic molecular bands still do not fit satisfactorily (Ekberg et al., 1986); also dust emission and absorption make these comparisons uncertain.

3. DETERMINATION OF FUNDAMENTAL PROPERTIES OF STARS

Obviously, a main objective for synthetic photometry is the use of calculated colours for the determination of fundamental parameters of stars. When determining effective temperatures the infrared-flux method of Blackwell and Shallis (1977), Blackwell et al. (1979), may well be superior in principle, at least as a primary method for calibrating relations between colours and effective temperatures. In particular, this method is much less dependent on the errors in the model atmospheres than are usual calculated colour indices. However, also this method requires calculated colours or fluxes. More important is that, in many applications there is no need for an effective temperature as such, but for a measure of the characteristic temperatures and the temperature gradient in the layers in which the stellar spectrum is formed. Thus, in stellar spectroscopic analyses it may well be more adequate to use calculated and observed colours when choosing the appropriate model for a particular star than to rely on the IR flux method, for which the effects of the temperature structure of the model are less and more indirect.

For determinations of surface gravities the use of colours (e.g. of the c_1 index of the uvby photometry for F stars) may require one order of magnitude less photons counted that spectroscopic methods, measuring ionization equilibria or damping wings of strong lines. However, various phenomena may affect the colours (see, e.g., the discussion of "the Hyades anomaly" in the c_1 index by Strömgren et al., 1982), and this may be one reason why empirical calibrations of photometric gravity measures, based on spectroscopic gravities (e.g. from damping wings) are important as checks and complements to calibrations with synthetic colours. Another reason for this is, for the c_1 index and several other gravity indicators, the problems with calculating the ultraviolet line-blocking with a satisfactory accuracy.

Similar comments are appropriate as regards measures of over-all metal abundances [Me/H]. In general I would prefer empirical calibrations of such measures, if they are based on homogeneous sets of high-resolution high-S/N spectroscopic standards, which now become available (cf., e.g., Nissen et al.,1985 but also Nissen, 1981) instead of using synthetic colours for this purpose. The latter are however very useful as complements and illustrate what is actually measured by the colours as regards abundances of different metals, sensitivity to microturbulence and other fundamental parameters, etc.

The possibility to determine abundances photometrically of other elements than those of the iron-peak also exist, at least for late-type stars for which molecular bands may serve as abundance indicators. Early examples of this possibility were provided by Bell, Dickens and Gustafsson (1979) and Dickens, Bell and Gustafsson (1979) in the use of the DDO system for discussing abundances of carbon and nitrogen of globular-cluster giants. Here, and in the study of Population I giants by Bonnell and Bell (1982), synthetic photometry is used for calibrating the colours. Another example is the theoretical calibration of an infrared CO index, measuring the strength of the first overtone CO bands in M giants, by McWilliam and Lambert (1984).

Other fundamental properties than the classical "three parameters" may also be studied photometrically, with theoretical calibrations. Thus, there is some chance to determine radii and masses separately for late-type giants because of the extension effects (Scholz, 1985). Strong magnetic fields affect the pressures and the blanketing and thus the colours of Ap stars (Carpenter, 1985). The rotation of early-type stars affect the uvby colours in a measurable way and this may be calibrated by calculations (cf. Collins and Smith, 1985). Winds of O-type stars produce an infrared excess (e.g., Castor and Simon, 1983) and mass-loss and circumstellar shells also affect the colours of many other stars. Deep chromospheres may also be seen in ultraviolet and far infrared colours as well as in molecular-band indices (Steiman -Cameron, Johnson and Honeycutt 1985). In order to trace phenomena of this character and to transform the measures to quantitative determinations of physical properties,detailed synthetic photometry is often necessary and convenient.

It should be stressed that even if the final calibrations of a colour system in terms of stellar fundamental parameters often will be empirical (e.g., based on fundamental-parameter determinations from high-resolution spectroscopy) the synthetic photometry may give key information about the form of the calibration relations. Often the relations between colours and fundamental parameters are highly non-linear (an obvious example is any measure of the strength of the blue CN bands, cf. Paper I), and a simplified assumption of a linear relation could be disastrous.

Similarily, the calibrations are often extrapolated, to more distant and exotic stars. At such extrapolations (for instance to less metal-rich, or more metal-rich stars than those seen or recognized in the solar neighbourhood) synthetic photometry is a necessary tool. A related application is the prediction of the appearance of stars of particular types which have not yet been identified but are supposed to be present. An early example of this use of theoretical colours is the prediction of uvby indices for horizontal-branch stars of Intermediate Population II, discussed by Gustafsson and Ardeberg (1978). Obviously, a related future use of synthetic photometry will be in the analysis of integrated colours of stellar systems, where stars of types not seen in the solar neighbourhood, or even non-existing in the Galaxy, may be expected to be present and contribute to the light.

4. STUDYING THE PROPERTIES OF COLOUR SYSTEMS

A question which is natural to ask photometrists but which often remains both unasked and unanswered is: "What is actually measured?" What is the reason for the sensitivity of a particular index to a particular physical parameter? Why is, e.g., the colour index f in the Brorfelde gnkmf photometry so sensitive to gravity? Or, what causes the blue deficiency in metal-poor late-type dwarfs (Hartwick, Cowley and Mould, 1984) or the broad-band colour differences between M supergiants of different metallicity (Elias, Frogel and Humphreys, 1985), or the behaviour in the IR colour diagrams of the K giants in the Nuclear Bulge (Frogel, Whitford and Rich, 1984)? The first of these questions has got an answer from studies with synthetic colours (Paper I) while answers to the others still are tentative or non-existing.

Another important application of synthetic photometry is the calculation of transformations between different colour systems. This has not yet been tried very much and needs systematic testing . An important advantage with this technique, as a complement to the normal empirical method, is that it reveals non-linearities, dependences on various parameters and the sensitivity to uncertainties in the transmission profiles (e.g., caused by variable water vapour in the atmosphere). An unpublished study of Bell (1985) on the R-I colours of various broad-band systems is a very good illustration to this possibility (cf. also Bessell, 1983). A similar application is the study of how a new set of filters (or spectrometer slots, cf. Manfroid, 1984) reproduces an older photometric system; another one is the calculation of effects of terrestrial extinction and interstellar reddening. One illustration to this is the demonstration in Paper I that the extinction coefficient in U-B is severely dependent on stellar metal abundance. Other important applications are studies of the properties of the filter systems at the Hubble Space Telescope, including investigations for the filters in the optical wavelength region of the effects of atmospheric extinction, in order to correct the ground-based calibration efforts of the new systems to conditions outside the Earth's atmosphere.

A final very important use of synthetic photometry is the comparative study of the efficiency of different photometric systems. Again, this application was developed and demonstrated in Paper I. It is thus possible to get assistance from theory, not only in selecting the most suitable photometric system among existing ones for a certain astrophysical task, but also when designing an entirely new photometric system. This possibility has, as yet, only been exploited in rare cases, which is in fact rather embarrassing, in particular in major projects like the choice of filter systems for the WF/PC of the Hubble Space Telescope. Admittedly, synthetic photometry is not yet producing ultimate calibrations of any photometric system in terms of temperature, gravity, metal abundance or other fundamental parameters. However, to abstain from the possibilities that this tool offers anybody who wants to find the best possible solutions or make well-educated guesses, seems unnecessarily foolish.

5. CONCLUSIONS

Instead of answering the (unnecessary) question put forward in the introduction as regards the need for observing stellar colours, I hope that the present discussion has demonstrated the need for calculating model colours. In fact, why should we not make the best possible observations? This often necessitates the use, and further development, of synthetic photometry.

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