6. THE STELLAR EFFECTIVE TEMPERATURE SCALE

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COOL STAR EMPIRICAL TEMPERATURE SCALES

MICHAEL S. BESSELL
Mt. Stromlo & Siding Spring Observatories,
Private Bag, Weston Creek PO, ACT 2611, AUSTRALIA

1. Introduction

The empirical temperatures scale for cool stars is generally well established. Temperatures are now known with reasonable precision for stars covering the range of spectral types from A to M. In the historical paper by Code, Davis, Bless and Hanbury Brown (Code et al. 1976), six stars between 10000K and 6500K had radii measured by the intensity interferometer and these six, together with the sun formed the basis of the empirical temperature calibration at the time. Since then, many temperatures have been derived for A-K stars (Blackwell & Lynas-Gray 1994; Alonso et al. 1996a) using the Infra-Red Flux Method (see Megessier 1994,5 and this volume), while lunar occultations (Ridgway et al. 1980) and more recently Michelson interferometry (Di Benedetto & Rabbia 1987; Dyck et al. 1996), have been used to measure the radii of K and M giants. It is a tribute to Hanbury Brown's Intensity Interferometer that temperature scales based on its measurements are essentially unchanged by the new data.

The empirical temperatures of metal-deficient and metal-rich stars had been virtually non-existent, but very recently, the IRFM has been applied by Alonso et al. (1996a,b) to a sample of such stars with excellent results.

There are however, some kinds of stars where the empirical temperature scale is not as well established. For M dwarfs, eclipsing binaries provide temperature for only 2 stars although the IR flux method has been used for a few additional M dwarfs (Tsuji et al. 1995, 96a).

Significant advances have also been made in atmospheric modelling for cool stars incorporating improved metal-line and molecular line opacities. Synthetic spectra and synthetic photometry generated from these models show good agreement with the empirical temperature scales and now allow us to confidently extend the temperature calibrations to stars over the full range of parameter space. We will discuss and illustrate some of those comparisons here.

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Fundamental Stellar Properties: The Interaction between Observation and Theory, 127–136.

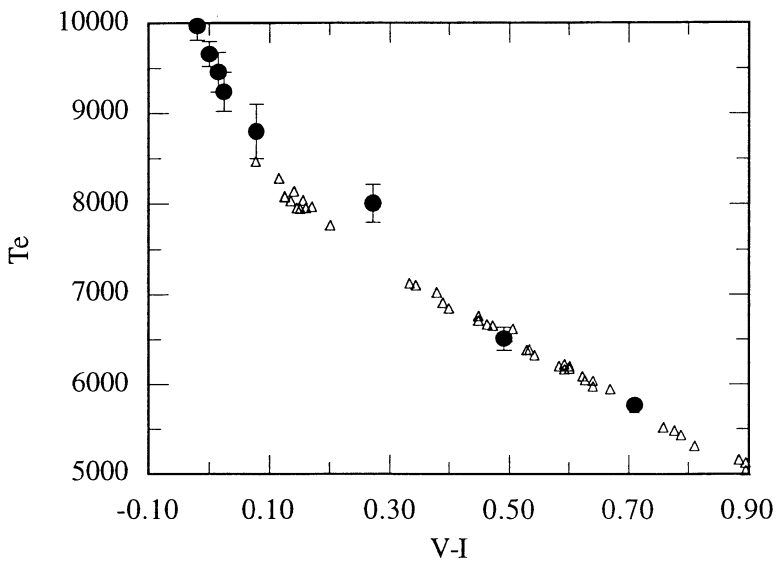

Figure 1. Closed circles with error bars are data from Code et al. (1976); without error bar, the sun. Open triangles are dwarfs from Blackwell & Lynas-Gray (1994).

2. Empirical temperatures

2.1. A–G DWARFS

In Fig. 1 is shown the comparison between the Code et al temperatures for A-F stars and those for the hotter stars measured with the IRFM by Blackwell & Lynas-Gray (1994). The colour index V-I in the Cape-Cousins system is used for the abscissa. These data are in excellent agreement except for Alpha Aql. In Fig. 2 all the Blackwell & Lynas-Gray (1994) temperatures are plotted against V-K. There is impressively little scatter about the mean locus.

2.2. K–M GIANTS

A few years after Code et al. published their main sequence stellar radii, another important paper was published by Ridgway, Joyce, White & Wing (1980) on the radii of red giants measured by lunar occultations. This paper has essentially defined the temperature scale for red giants over the past 17 years. However, Michelson interferometer observations of red giants have recently produced more precise angular diameters and in the future we look forward to this technique delivering very precise radii for most kinds of stars. In Fig. 3 are shown the best data from Ridgway et al. (1980) together with the Michelson interferometer data from DiBenedetto & Rabbia (1987). Although the precision of the occultation data was much lower than that of the Michelson data, the mean Te versus colour relations defined by the two data sets is almost identical. A comparison between the cool end of the Blackwell & Lynas-Gray (1994) IRFM based temperature calibration

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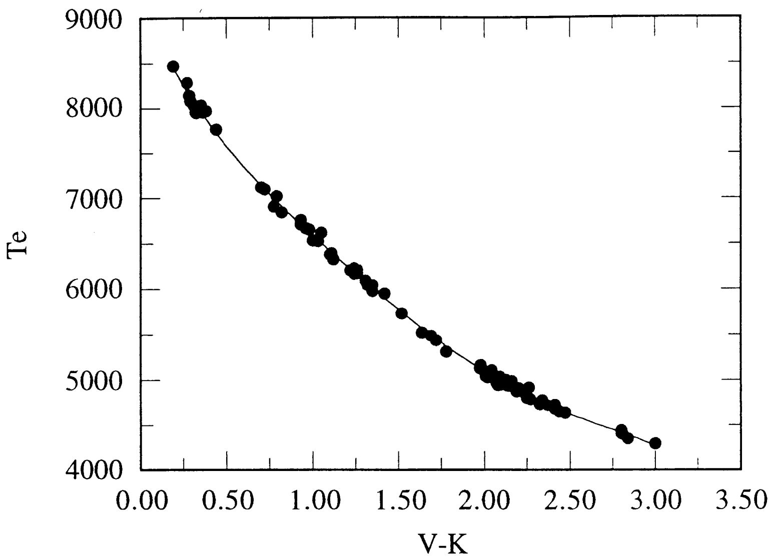

Figure 2. Closed circles are IRFM temperatures from Blackwell & Lynas-Gray (1994). The continuous line is a polynomial fit to the data.

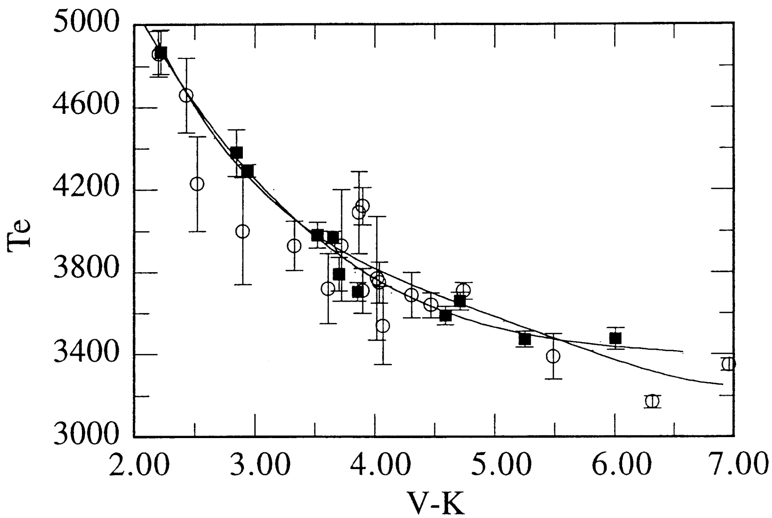

Figure 3. The Te versus V-K diagram for the best occultation data of Ridgway et al. (1980) and the Michelson interferometer data of Di Benedetto and Rabbia (1987) . Error bars in the measured temperatures are shown.

and the hot end of the occultation based temperature calibration from Ridgway et al. (1980) shows that the BLG94 scale is too hot below 4400K. Dyck et al. (1996) summarize the current temperature scale for the KM giants and supergiants and for the giants their result is essentially identical to that shown here. However, they also conclude that the K4.5 supergiants (luminosity I, II) are 400K cooler than giants of the same spectral type. I find this hard to accept because the fine analyses of several K supergiants that I have done indicate they have very similar temperatures to the giants. *It is of great interest to understand why the radii measurements of the supergiants indicates that they are much cooler.*

2.3. MIRA VARIABLES

Mira variables have very extended atmospheres resulting primarily from the radial pulsations driving shock waves through a cool low density atmosphere. Because Miras have the largest radii of any stars there have been direct measurements made over the years. These indicated that the radius was not unique but varied with wavelength. Such complications occur in other stars too but are not as great (see Scholz this volume). Modern interferometer radii measurements of Mira variables (eg. Haniff et al. 1995) support in general the earlier work but have still been difficult to interpret. The advent of more Michelson stellar interferometer programs working at several different wavelengths will provide an excellent database that will enable the remaining longstanding problems of Mira atmospheres to be better diagnosed.

A start to understanding the effective temperatures of Mira atmospheres has been made in a series of papers by Bessell et al. (1989, 96) where the theoretical structure of Mira atmospheres and their observational consequences have been explored. Whilst this is too complex a problem to summarise here, it has been possible to understand how cool (2200K-2400K) black-body temperatures are fitted to the near-IR spectra of Mira although the underlying effective temperature varies between 3050K and 2700K during the pulsation. It has also been possible to explain other observational anomalies between the spectra and colors of Mira variables and small-amplitude variables or non-variable stars. Much of this analysis has been only crudely quantitative because of the computational difficulties associated with handling the opacity from millions of lines in a moving atmosphere in order to generate more realistic synthetic spectra. More diameter measurements and more modelling is necessary to understand the complexities of Mira atmospheres but, in the meantime, the above papers do provide useful insights into the effective temperatures of Mira variables.

2.4. K–M DWARFS

The K and M dwarfs are such small objects that it is unlikely that ground-based stellar interferometers will ever be able to directly measure diameters. However, there is another way. There are two M dwarfs with measured diameters. These stars are members of eclipsing binaries where the occultation of one of the components by the other enables the diameters to be measured. Although the details of the orbits and the timings can be

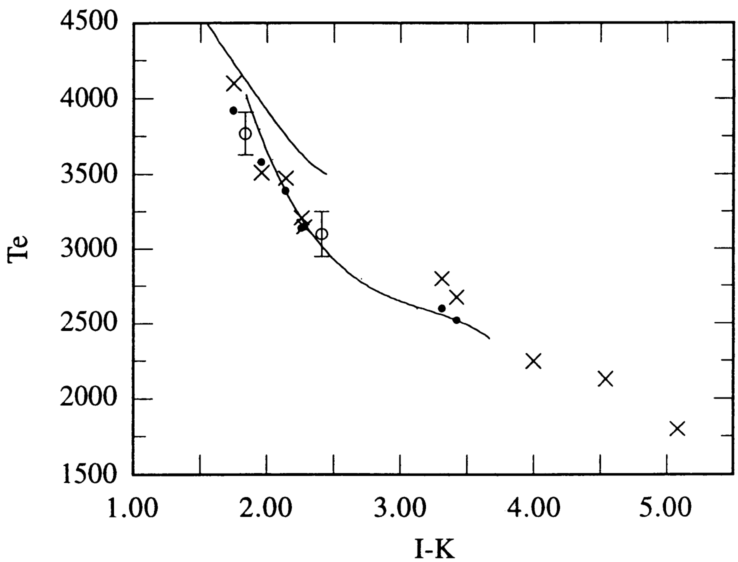

Figure 4. The comparison between model Te versus I-K color and the empirical temperatures for M dwarfs. The open circles with error bars are YY Gem and CM Dra; the crosses are IRFM data from Tsuji et al. (1995, 1996); the filled circles are Brett(1995a,b) fits to far-red spectra. The upper line represents the no-overshoot ATLAS9 models; the lower line represents the NMARCS models

very precise, the factor limiting the precision of the effective temperature is usually the parallax. New parallax measurements are badly needed for these stars. The two stars are YY Gem (3770± 200K) (Kron 1951; Habets & Heintze 1981) and CM Dra (3120± 150K) (Lacy 1977; Metcalfe et al. 1996). CM Dra, rather unfortunately has halo kinematics but its spectrum suggests that its metallicity is not more than a factor of 3 less than solar. Its halo nature should be remembered, however, when using it as a temperature standard. Popper (1993, 96) has reported several other possible F-K eclipsing binaries whose orbits should be worked on. None of these are cooler than CM Dra.

Tsuji et al. (1993, 96) has used the IRFM to deduce the temperature of some M dwarfs. These temperatures, which extend from 4000K to 1600K, are in excellent agreement with the two eclipsing binary star temperatures. Brett (1995a,b) derived temperatures for some M dwarfs from fitting the spectra to his model spectra. In Fig. 4 are plotted the empirical temperatures together with some theoretical colour temperature relations from model atmospheres and Brett's spectral fitting. The model atmospheres will be discussed below.

3. Model atmosphere color-temperature relations

a) The Kurucz-Castelli ATLAS9 models

Kurucz (1993) has made available models, hydrogen line profiles, spectra and colors for a large grid of temperatures, gravities and abundances. Wood and Bessell (1994) computed colors on the UBVRIJHKL system for these Kurucz spectra and these have been available via anonymous ftp as ubvrijhkl.dat.z from mso.anu.edu.au at /pub/bessell/. In the 1993 flux data there was evidence of some discontinuities in the computed colors of A-G stars. Castelli (1996) explained how to eliminate these discontinuities which were related to a modification of the mixing-length convection adopted by Kurucz(1993) for computing the 1993 models and called by him "approximate overshooting". The 1995-1996 Kurucz models were recomputed by adopting the improvement suggested by Castelli for the approximate overshooting. Castelli (1996) has also recomputed the same set of models but with no-overshoot and for $l/H = 1.25$ (Castelli 1995). Castelli, Gratton & Kurucz (1996) discussed the differences yielded by the overshoot and no overshoot models on some color indices and on Balmer profiles. They showed that the overshoot solar model fits the solar spectra better than the no-overshoot solar model, but that the no-overshoot models should be preferred for stars different from the sun. The no-overshoot ATLAS9 models are available from castelli@astrts.oat.ts.astro.it.

b) The NMARCS models.

The new revised MARCS program incorporating statistical line opacities has been used by Plez, Brett and Nordland to model M giants and dwarfs. Plez, Brett & Nordland (1992) and Plez (1996) modelled giants while Brett and Plez (1993) and Brett (1995a,b) have modelled the M dwarfs. These models are available from plez@nbivax.nbi.dk. The colors and bolometric corrections of these models are discussed by Bessell et al. (1970). A complete grid (A–M stars) is currently being computed by Gustafsson et al. (1997).

3.1. A–K DWARFS

In Fig. 5 are shown the no-overshoot ATLAS9 model Te versus V-I relation in comparison with the BLG94 IRFM data. In Fig. 6 is shown the comparison between the model temperature V-I color relations and the empirical relations. Another model comparison in I-K for the M stars was shown in Fig. 4. There is quite good agreement between the model temperatures and the empirical temperatures. The ATLAS9 models are seen to be less reliable for temperatures below 4250K. The published NMARCS M dwarf models are suspect below 2800K due to inadequate H_2O opacity. Brett (1995a,b) used a smoothed empirical treatment of H_2O opacity for these preliminary models but in the NMARCS grid currently being computed, H_2O opacity will be incorporated on the basis of the more than 20 million lines that have recently been computed by Jorgensen (1996) and we anticipate much better agreement. Models by Allard et al. (1994) had similar problems with water but new models being computed will also incorporate the new opacities.

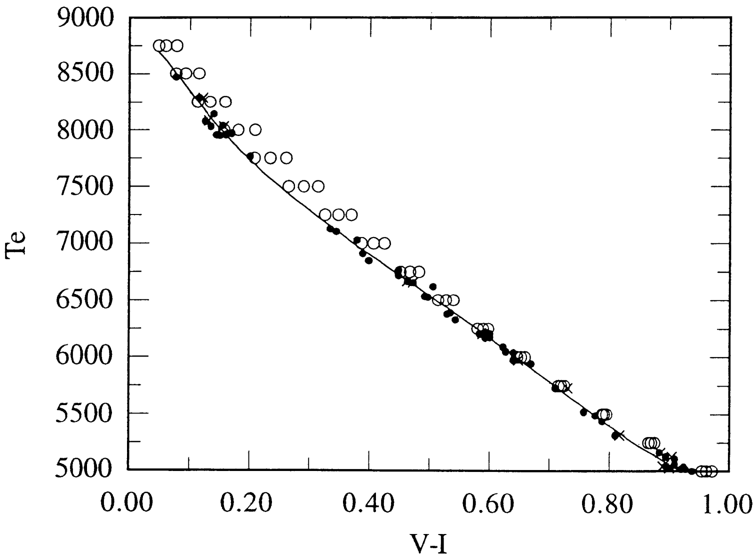

Figure 5. Comparison between model temperatures derived from V-I colors and the IRFM temperatures for A-G stars. The crosses indicate measured V-I values; the filled circles are transformed V-I values from V-K. There is no obvious separation of the data points. Model colors from ATLAS9 no-overshoot models are plotted for log g = 4.5, 4.0, 3.5; higher gravity gives redder color.

However modelling of the atmospheres of the coolest M dwarfs requires in addition the inclusion of grain opacities and an understanding of how grains form and segregate (see Tsuji et al. 1996b).

3.2. K–M GIANTS AND SUPERGIANTS

In Fig. 7 are compared the observed and model Te versus V-K color relation for the KM giants. The plotted observational data are from Blackwell & Lynas-Gray (1994) and Di Benetto & Rabbia (1987). The continuous line is the mean empirical relation discussed above. The model colors are in extremely good agreement with the observations even given the complication of a range in model color depending on gravity and extension. The models predict temperatures to better than 100K between 5000K and 3200K. Below 3000K all giants are variable, many of them Mira or long-period variables. The colors of cool models are affected not only by temperature, gravity and abundance but also by mass (or sphericity). For temperatures between 4000K and 3400K the effect of mass is comparable or greater than the effect of gravity on the V-K color but below 3200K the effect of gravity is very great. Accurate Michelson interferometer radii for late-M stars with known abundances and a range of masses will enable such predicted variation in the color-temperature relations to be tested. More discussion of the model colors are given in Bessell et al. (1997).

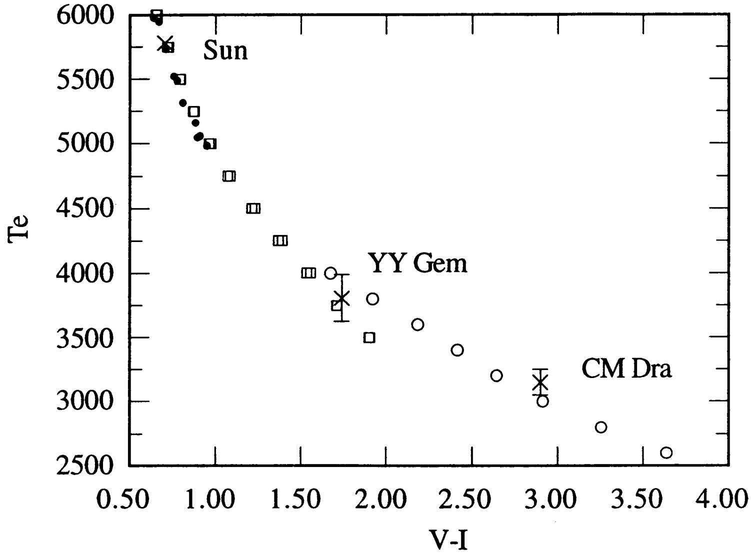

Figure 6. Comparison between model temperatures derived from V-I colors and the empirical temperatures for G-M dwarfs. The dwarfs with IRFM temperatures are plotted as solid circles. The dwarfs with directly measured radii (large crosses with error bars) are the sun and the eclipsing binaries YY Gem and CM Dra. The ATLAS9 no-overshoot models for log g =4.5 and 4.0 are indicated by open squares; the open circles are the NMARCS models for log g = 4.5.

4. Distances and Bolometric Corrections

Parallaxes provide the fundamental distances to the nearest stars, in particular to the low mass K-M dwarfs and white dwarfs. Lists of parallaxes are available in the Yale Parallax Catalog (Van Altena et al. 1995) and in other catalogs such as the 3rd Gliese & Jahreiss (1996) Catalog. The US Naval Observatory (eg. Monet et al. 1992) and the University of Virginia (eg. Ianna et al. 1996) continue strong ground based CCD programs to provide parallaxes for intrinsically faint stars. However, the HIPPARCOS satellite (Perryman et al. 1995) is producing extremely accurate parallaxes for bright stars which will revolutionize our knowledge of the upper main sequence. The catalog is expected to be available in 1997.

Bolometric corrections are required to enable comparison between theoretical HR diagrams and colour-magnitude diagrams. Bolometric corrections have historically been used to correct the visual magnitude to the bolometric magnitude (ie the luminosity) but the term nowadays refers to the magnitude correction to apply to any passband. The bolometric correction is defined as $M_{bol} = M + BC_M$ where M refers to a particular passband magnitude. The bolometric correction zeropoints are arbitrary but have usually been defined so that no star has a positive visual bolometric correction or else have adopted some particular visual bolometric

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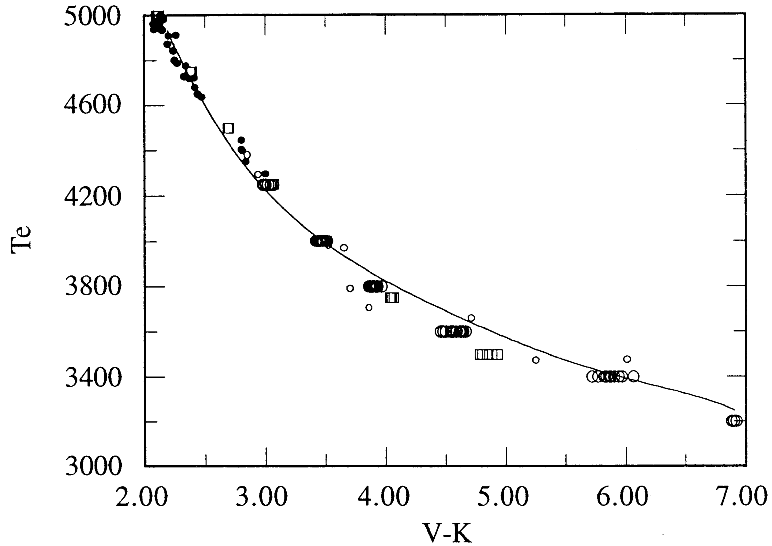

Figure 7. Comparison between model temperatures derived from V-K colors and the IRFM and interferometer temperatures for GK stars. The closed circles are IRFM data; the small open circles are Michelson interferometer data. The open squares are ATLAS9 no-overshoot model colors for log g = 0.0, 0.5, 1.0, 1.5; the large open circles are NMARCS models for the same gravities.

correction for the sun. This leads to lots of confusion in the literature. We support the proposal to adopt a bolometric correction (BC_V) of -0.07 mag for a solar model. But note that this zeropoint is different to that of -0.194 adopted by Kurucz (1979) and followed by Schmidt-Kaler (1982). We recommend that the theoretical bolometric corrections from the ATLAS9 and NMARCS models be used. These are in good agreement with empirical corrections and are available for a wide range of temperatures, gravities and abundances. They are discussed in Bessell et al. (1997) and available by anonymous ftp from the authors.

References

Allard F., Hauschildt P.H., Miller S., Tennyson J. 1994, ApJ 426, L39

Alonso, A., Arribas, S., Martinez-Roger,C. 1996a A&AS 117, 227

Alonso, A., Arribas, S., Martinez-Roger,C. 1996b A&A 313,873

Bessell M.S., Brett J.M., Scholz M., Wood P.R. 1989, A&A 213, 209

Bessell M.S., Scholz M., Wood P.R. 1996, A&A 307, 481

Blackwell D.E., Lynas-Gray A.E. 1994, A&A 282, 899

Brett J.M. 1995a, A&A 295, 736

Brett J.M. 1995b, A&AS 109, 263

Castelli F. 1995 Private communication.

Castelli F. 1996 Proceedings of the Workshop on Model Atmospheres and Spectrum Synthesis, Vienna July 1995, ASP Conference Series, ed. S. Adelman, F. Kupka & W. Weiss In press

Castelli F., Gratton R., Kurucz R.L. 1997 A&A 318, 841

Code A.M., Davis J., Bless R.C., Hanbury Brown R. 1976, ApJ 203, 417
DiBenedetto, G.P., Rabbia, Y. 1987, A&A 188, 114
Dyck, H.M., Benson, J.A., van Belle, G.T., Ridgway, S.T. 1996, AJ 111, 1705
Gustafsson B., Plez B., Edvardsson B., Eriksson K., Nordland A., 1997 in preparation
Gliese, W., Jahreiss, H. 1996, private communication
Habets G.M.H.J., Heintze J.R.W. 1981, A&AS 46, 193
Jorgensen, U. Grae-, 1996, Private communication
Kron, G.E. 1952, ApJ 115, 301
Kurucz R.L. 1979, ApJS 40, 1
Kurucz R. L. 1993, CD-ROM No 13.
Kurucz R.L 1995-1996 in preparation
Lacy C.H. 1977, ApJ 218, 444
McWilliam, A. 1990, ApJS 74, 1075
Megessier C. 1994, A&A 289, 202
Megessier C. 1995, A&A 296, 771
Metcalfe, T.S., Mathieu, R.D., Latham, D.W., Torres, G. 1996, ApJ 456, 356
Monet et al. 1992, AJ 103, 638
Perryman, M.A.C. et al. 1995, A&A 304, 69
Plez B., Brett J.M., Nordlund A. 1992, A&A 256, 551
Ridgway S.T., Joyce R.R., White N.M., Wing R.F. 1980, ApJ 235, 126
Schmidt-Kaler Th. 1982, in: Landolt-Brnstein, Numerical Data and Functional Relationships in Science and Technology, Vol. 2. (eds.) K. Schaifers & H.H. Voigt Springer-Verlag, Berlin
Tsuji T. 1981b A&A 99, 48
Tsuji T., Ohnaka K., Aoki W. 1996a, A&A 305, L1
Tsuji T., Ohnaka K., Aoki W. 1996b, A&A 308, L29
Wood P.R., Bessell M.S. 1993 Private communication by anonymous ftp

DISCUSSION

DAVID ARNETT: What about the M supergiants?

MIKE BESSELL: Dyck et al. (1997) claim that the M supergiants are also cooler than M giants of the same spectral types by about 150K. However, I find that like the K supergiants, the early M supergiants seem to follow the same Te versus V-K as the giants. But the models do indicate that there should be differences in the temperature color relation due to gravity in the mid to late M giants.

GIUSEPPE BONO: The discrepancy between the theoretical atmosphere models and observational data in the temperature color relations you showed could be due to the fact that in this temperature range the stars should be located inside the instability strip.

NICHOLAS ELIAS: Are the effects of starspots taken into account for M star calibration?

MIKE BESSELL: No. All the models are homogeneous, plane parallel or spherically symmetrical atmospheres and convection was handled using the mixing length technique. It is true that star spots will affect the colors of M dwarfs but I think mainly in the UV and blue. Colors obtained in the far-red and near-IR should be good effective temperature indicators. In our Mira models we have also neglected the the non-LTE aspects of the shock front, such as the emission lines in the computation of synthetic spectra or colors.

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