A GENERAL CONFRONTATION BETWEEN SOLAR DATA AND SOLAR MODELS

R. A. BELL AND M. J. TRIPICCO
Department of Astronomy
University of Maryland
College Park, MD 20742, USA

1. Introduction

Since its effective temperature, surface gravity and chemical composition are well established, the Sun has often been used for tests of model stellar photospheres. There are two important potential tests – firstly, comparisons of observed and calculated line spectra and, secondly, comparisons of observed and calculated fluxes. If solar model calculations can successfully reproduce both of these data sets, then it gives confidence in the quality of models of other cool stars. However, different observations of solar fluxes do not agree with one another with the precision required in testing solar models.

Previous comparisons of models and the Sun have used the Labs & Neckel (1968, 1970) data for the Sun, these being most recently presented by Neckel & Labs (1984, hereafter NL84). However, other measurements have been made e.g. by Arvesen, Griffin & Pearson (1969, hereafter AGP), who observed from a high flying aircraft, and by Lockwood, Tug & White(1992, hereafter LTW), who compared the Sun to the spectrophotometric standard Vega, using a pinhole to reduce the solar flux so that it could be studied with a stellar instrument. Unfortunately, the LTW data are not corrected for the presence of telluric lines.

The systematic differences between these different measurements are surprisingly large. The ratio of the LTW to the NL84 data is greater than unity for $\lambda < 5500$ Å, reaching a maximum of about 1.1 at 4000 Å, and less than unity for $5500 < \lambda < 8500$ Å, reaching a minimum of 0.95. The LTW data match the AGP data reasonably well for $\lambda < 5500$ Å and are somewhat fainter at the shorter wavelengths.

K. G. Strassmeier and J. L. Linsky (eds.), Stellar Surface Structure, 527–537.

Some years ago, Gustafsson & Bell (1979, GB79) compared computed fluxes with the Labs & Neckel solar irradiance. The models were too bright in the ultra-violet, more successful at somewhat longer wavelengths and then too faint further towards the infra-red. GB79 studied this effect in other stars, finding that the discrepancy increased with decreasing T_{eff} and increasing metal abundance. They concluded that the most plausible explanation for this was incomplete blocking in the synthetic spectra, due to the missing "veil" of weak lines suggested by Holweger (1970). Kurucz (1979) made similar comparisons, commenting in particular on the effect of his omission of molecular lines.

In the intervening period, Kurucz (1991) has made more extensive calculations of atomic oscillator strengths. He has constructed new grids of model photospheres and synthetic fluxes (Kurucz 1992a). Newer model fluxes showed much better agreement with the Labs & Neckel data and on the basis of this, Kurucz (1992b) argued that the problem of the missing opacity was solved. Subsequently, he has made more recent calculations of photospheres and colours available on CD-ROM (Kurucz 1993a, 1993b), including a model of the Sun.

Bell, Paltoglou & Tripicco (1994,BPT94) presented calculations of synthetic solar line spectra and compared their results with the high resolution solar atlas of Kurucz et al (1984). They showed that the Kurucz (1991) list predicted many lines which were either not visible in the solar spectrum or were much weaker than predicted. Since the energy levels of these lines are often predicted and not observed, the wavelengths are not very good. Nevertheless, it is clear that the Kurucz (1991) list, at least in the form used by BPT94, predicts many more lines than are not observed than the contrary i.e. the predicted spectrum does not miss as many lines as it erroneously predicts. On the basis of this, BPT94 disputed the claim that the problem of the missing solar opacity had been solved. They argued that successful resolution of this problem required not only matches of solar fluxes, which have a resolution of a few Å but also matches of detailed line spectra. Bell & Tripicco (1994) subsequently computed further spectra allowing for autoionization, which occurs for some of the erroneous lines. While they found that the discrepancy between observed and calculated spectra was not so obvious, and the inaccurate wavelengths make the problem less certain, some of these autoionizing lines would be expected to be visible and are not. Other high resolution comparisons of solar spectra are given by Briley et al. (1994) and Tripicco & Bell (1995), the latter also giving comparisons with Arcturus.

The different sets of observational data are intercompared in Figs. 1. and 2. All subsequent comparisons with models are made using the LTW data.

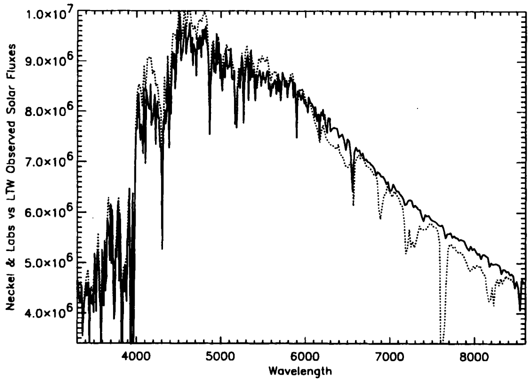

Figure 1. The Neckel & Labs (1984, solid line) and Lockwood, Tug & White (1992, dashed line) solar flux data are compared

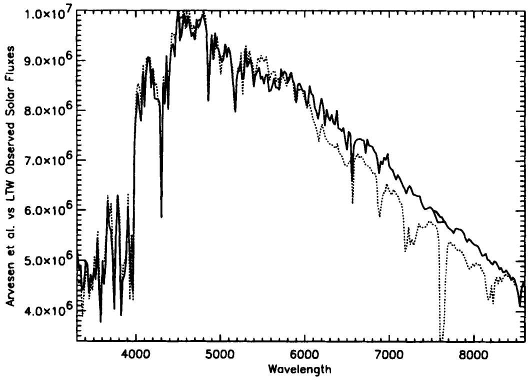

Figure 2. The Arvesen, Griffin & Pearson (1969, solid line) and Lockwood, Tug & White (1992, dashed line) solar flux data are compared

Three high spectral resolution solar atlases are available – those of Delbouille, Neven & Roland (1973), the Kitt Peak Preliminary Solar Atlas of Brault & Testerman (1972) and the National Solar Observatory digital atlas (Kurucz et al. 1984). The last has been particularly useful in tests of the corresponding synthetic spectra, in view of the ease with which com-

https://doi.org/10.1017/S0074180900083558 Published online by Cambridge University Press

parisons can be made. We have used the line blocking computed from the Kurucz et al. atlas, the latter being derived under the assumption that the continuum is accurately located. The continuous fluxes of the models and this observed line blocking have been compared with the observed fluxes.

The purpose of the present paper is to compare the fluxes and line spectra calculated using a single line list – an improvement of the BPT94 list – with the observations. These calculations have been carried out using models calculated with different versions of the MARCS program (Gustafsson et al., 1975), with the Holweger-Muller solar model and with the Kurucz solar model (Kurucz 1993a). The continuous fluxes used in these calculations included H^- (Wishart 1979 and Bell & Berrington 1987), atomic hydrogen, FeI bound-free (Dragon & Mutschlecner 1980, hereafter DM80), and MgI and SiI bound-free, this latter data being part of the Opacity Project calculations (Seaton, private communication). The calculations presented here cover the wavelength region 3000−8800 Å.

The Opacity Project data was compared with the values used earlier i.e. the values compiled by Mathesen (1984). There can be considerable differences between the two i.e. the Opacity Project absorption coefficient for the MgI 4s ^{3}S state is 1000 times larger at 3500 Å. Because of this difference, because of the paucity of levels included in the DM80 calculations, and because of evidence that the continuous opacity is underestimated shortward of 3600 Å, some of the subsequent calculations were carried out with the FeI opacity being increased.

2. Calculations and comparisons

MARCS models were computed at Maryland using different values of the mixing length ($\alpha = l/H = 1.2$, 1.6 and 1.8) and the convective efficiency factor y (0.076 and 0.333). Overshooting was not included. While the $T-\tau$ (5000Å) relations of these models showed large differences for $\tau > 1$, the fluxes did not vary appreciably over the wavelength range considered here, and will not be discussed further. Since the initial model flux calculations were too bright shortward of 3500 Å, additional calculations were made with the FeI bound-free opacity being increased. The coding of the Maryland MARCS models used subsequently is (T_{eff}, ξ, FeIx), with ξ being the turbulent velocity. and FeIx being the increase in the FeI b-f opacity.

The $T(\tau)$ differences between a reference MARCS model (5780,1.0,1.0), a MARCS with y=0.333, a MARCS model calculated in Uppsala using opacity sampling (Edvardsson, private communication), the Holweger-Muller and Kurucz models are given in Fig. 3. The differences in the models at depths of log τ(5000Å) > 0 are due to different treatment of convection, at least for MARCS models, with the inclusion of overshooting in the Kurucz model

https://doi.org/10.1017/S0074180900083558 Published online by Cambridge University Press

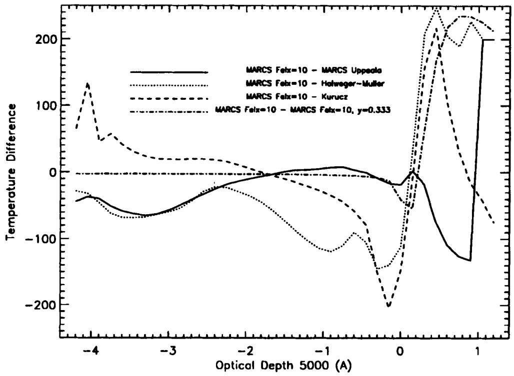

Figure 3. The differences between the T$-\tau$(5000Å) relations of various models and the Marcs model with (5780,1,1) are compared

also playing a role.

The LTW data are given for 6Å or 12 Å intervals. When such data is compared to the calculations, mismatches can occur owing to small errors in the wavelengths of the observations. This contributes scatter to the comparison. The LTW data is consequently smoothed over 30 Å or 60Å bins before making comparisons.

The LTW data and the spectrum of a standard Maryland **MARCS** model (5780,1.0,1.0) are compared in Fig. 4, the observed fluxes being converted to values that would be seen at the sun's surface. In order to see if the data at wavelengths greater than 6000 Å could be used, the telluric line spectrum longward of 6000 Å was modelled using the HITRAN database and the SAAG3 program (Stevenson 1994). Comparisons with the digital solar atlas showed good agreement, after an appropriate water vapour content had been found. The modelling shows that the telluric lines are negligible in the windows at 6600, 7000, 7500 and 8500 Å. It is obvious that this model would give a good fit between 4000 and 8600 Å except that it is about 3The fit to the data in the in the 3900−4000 Å region is influenced very much by the CaII H and K lines, and by the treatment of their damping, and so does not give a good test of the model fluxes. However, the Sun appears to be brighter than the model here while the fit of the spectrum below 3600 Å is particularly disappointing.

Comparisons of this kind are are very good thermometers, because a model with T_{eff}=5760K is 5Å.

https://doi.org/10.1017/S0074180900083558 Published online by Cambridge University Press

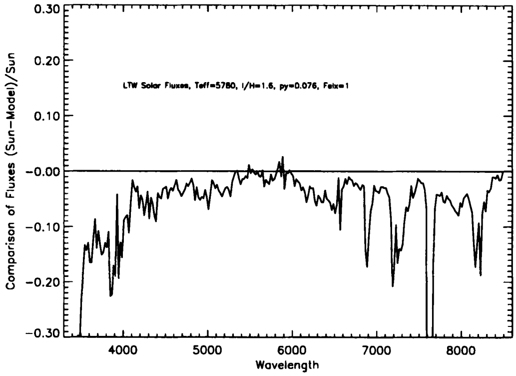

Figure 4. The fluxes of the standard Marcs model (5780,1,1) are compared with the observed fluxes of Lockwood, Tug and White. The ordinate is (Observed-Computed)/Observed

A comparison with Figs. 1 and 2 shows that this model would be a poor fit to the NL84 data in the 4000−4300 Å region, since these data are as much as 10% fainter than the LTW data here.

At this point, we ask whether or not this poor fit is due to a poor computation of line blocking. Fig. 5 shows a sample comparison of the two line spectra in this region. It is obvious that the fit of the two is by no means perfect. In particular, there is a very curious depression of the observed continuum in the 3480−3490 Å region (this is also present in the Delbouille et al. Atlas). However, the error in the computed line blocking seems to be too small to cause such a substantial error in the computed fluxes in this wavelength region.

To study this point further, we constructed some "calculated" fluxes which are based upon the model continuous fluxes and the observed line blocking, the latter being derived from the NSO digital atlas. These have been compared with the observations in Fig. 6. The pattern is again interesting, in the sense that that the fit is good for wavelengths in the 4000−6000 Å region, the disagreement between 6000 and 6500 Å is more apparent and the disagreements in the regions affected by telluric lines cancel to a major extent. (The water vapor line absorption is presumably different in the NSO Atlas data and the LTW data.) However, and more importantly, the fit shortward of 4000 Å is as bad as before.

There are three obvious ways of explaining this poor fit in the UV. One is that the measurements of the observed line blocking are wrong. The

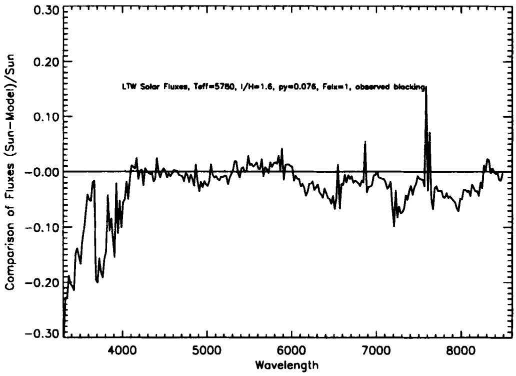

Figure 5. The computed line spectra (dashed line) for a model (5760,1,10) and the observed solar line spectrum (Kurucz et al. 1984) are intercompared

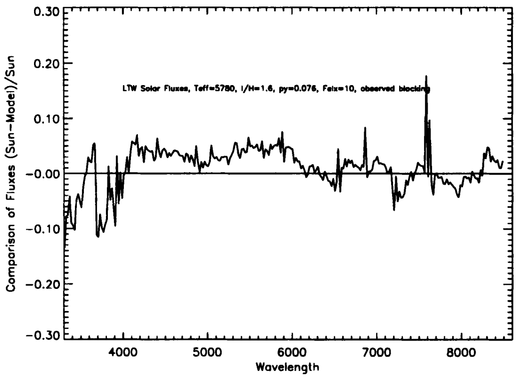

Figure 6. The Lockwood, Tug and White data is compared with that derived from the continuous fluxes of the model (5780,1,1) and the observed line blocking

second is that the calculated continuous fluxes are wrong. The third is that the observations are wrong.

As described in BPT94, the line data used has been altered in some cases to improve the fit between observed can calculated spectra. These alterations include changes in wavelengths and oscillator strengths. Changes

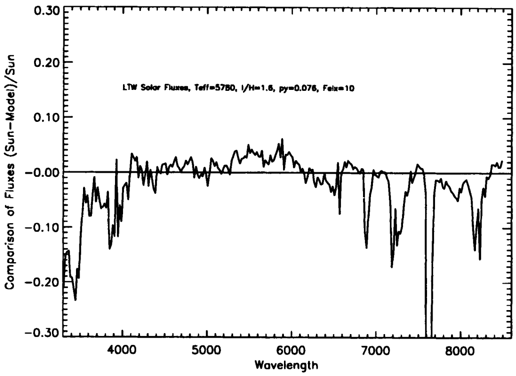

Figure 7. As Fig. 4, the calculations using FeIx = 10

of 0.1 in log gf for strong lines and 0.01 Å in wavelength are readily seen.The broadening theory used for the lines is simply a combination of van der Waals broadening and radiative broadening. The radiative damping values have been determined individually for the stronger lines and average values used for the weaker ones. No attempt has been made to improve the fit of line profiles, except by altering gf values. While it is clearly a challenge to draw a continuum in Fig. 5, the fit of the computed line spectrum, in the 3400−3450 Å region in particular, argues against a poorly located continuum. The line blocking would have to be increased by a significant factor to cause agreement in Fig. 6.

In order to see if the continuous fluxes could be altered appreciably in the ultraviolet, we calculated new models with the FeI bound-free opacity being increased by factors (FeIx) of 10 and 20. It is interesting to note that these opacity changes do alter the $T-\tau(5000\text{Å})$ relation of the models very slightly as well as the flux distribution with wavelength such that the T_{eff}=5780K models with enhanced FeI bf are 2% brighter in the 5000−6000 Å region. The fit of these models (Figs. 7, 8) is better at all wavelengths than is that of the standard model (FeIx=1) shown in Fig. 4. Nevertheless, the model with FeIx=20 is brighter than the LTW data by almost 20% at 3500 Å, a difference which reverses abruptly to about 4% between 3600 Å and 3800Å.

As one final experiment, the model calculations were repeated using a turbulent velocity of 1.5 km/s, instead of 1 km/s. This change alters the equivalent widths of the lines on the flat part of the curve of growth and,

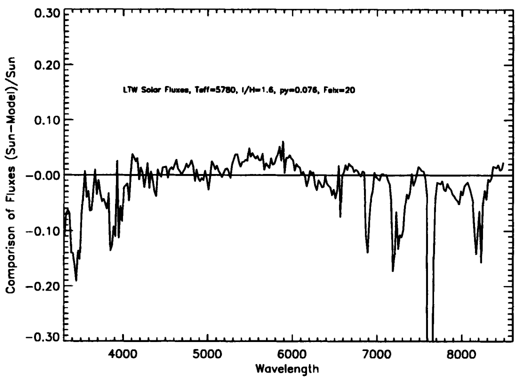

Figure 8. As Fig. 4, the calculations using FeIx = 20

as a result, the model becomes fainter at almost all wavelengths. Even with this change, the model is still brighter than the observations for $\lambda <$ 3500 Å and the sharp contrast in agreement longward and shortward this wavelength persists. While we have not determined the optimum value to use as the turbulent velocity of our models from curves of growth, work by Blackwell & Shallis (1979) suggests a value of 1 km/s is appropriate.

Since it is not obvious that further improvements can be made to the model fluxes, we now turn to a brief discussion of solar magnitudes and colours.

One motivation for performing these calculations was to test these models to see what the implications for the colours of stars would be. In order to do this, we calculated the U′, B and V magnitudes of the models and the observations using Bessell's (1990) sensitivity functions. We refer to the first magnitude as U′, since the LTW observational data set does not extend down to 3000 Å, the normal lower wavelength for the U band. The differences between the observations and the reference model (5780,1.0,10) are: U′ 0.172, 0.099, 0.117; B 0.063, 0.003, 0.013; V −0.001, −0.027, −0.033; with the observations being, in order, NL84, LTW and AGP. The magnitude differences then give B−V differences of 0.064, 0.030 and 0.046, respectively. Note that the MARCS models are predicting a B magnitude similar to that of LTW and AGP and a V magnitude close to that of the NL84 value.

If the colour zero point is defined by Vega and the Dreiling & Bell (1980) Vega model, the B−V colours of the models (5780,1.0,10), (5780,1.0,20) and (5760,1.0,20) are 0.598, 0.601 and 0.607, while these models, the Vega model and the appropriate geometrical dilutions gives solar apparent V magnitudes of −26.773, −26.774 and −26.756. The B−V colour differences translate into solar B−V colors of 0.662, 0.628 and 0.641. The observed values for B−V are 0.661 ± 0.003 and for V are −26.75 ± 0.06 (see Hayes 1985 for references). While the calculated B−V is bluer than the solar values, the difference is small for the LTW B−V.

The U′ values show how it would be even harder for Maryland MARCS models and synthetic spectra to fit the NL84 ultraviolet fluxes than the LTW or AGP ones.

3. Discussion

It is clear that further observations of the solar fluxes are required in order to settle the question of the fits of models. In addition, we also need to have confirmation of the values of the FeI bound-free absorption coefficient and, in addition, calculation of other metal absorption coefficients such as Ni and Cr. Other ways of checking the solar UV continuous absorption coefficient should also be tried. Finally, the solar fluxes should be compared with the fluxes of other G dwarf stars.

A more detailed discussion of this topic will be given elsewhere..

Acknowledgments. This work was supported by the National Science Foundation under grant AST93-14391.

References

Arvesen, J.C., Griffin, R.N.Jr. and Pearson, B.D.Jr. (1969) *Appl Optics*, **8**, 2215 (AGP)
Bell, K.L. and Berrington, K.B. (1987) *J. Phys. B.*, **20**, 801
Bell, R.A., Paltoglou, G. and Tripicco, M.J. (1994) *MNRAS*, **268**, 771
Bell, R.A. and Tripicco, M.J. (1995) in IAU Joint Discussion 16, *Astrophysical Application of Powerful New Atomic Databases,* A.S.P. Conference Series, No. 78, ed. by S.J. Adelman & W.L. Wiese, p. 365
Bessel, M. S. (1990) *PASP*, **102**, 1181
Brault, J. and Testerman, L. (1972) *Kitt Peak Preliminary Solar Atlas*, Kitt Peak National Observatory
Briley, M.M., Hesser, J.E., Bell, R.A., Bolte, M. and Smith, G.H. (1994) *AJ*, **108**, 2183
Delbouille, L., Neven, L. and Roland, G. (1973) *Photometric Atlas of the Solar Spectrum from λ3000 to λ10000*, Institut d'Astrophysique de l'Universite de Liege and Observatoire Royale de Belgique
Dragon, J.N. and Mutschlechner, J.P. (1980) *ApJ*, **239**, 1045
Dreiling, L. A. and Bell, R.A. (1980) *ApJ*, **241**, 737
Gustafsson, B., Bell, R.A., Eriksson, K. and Nordlund, Å. (1975) *A&A*, **42**, 407
Gustafsson, B. and Bell, R.A. (1979) *A&A*, **74**, 313
Hayes, D.S. (1985) in IAU Symposium 111, *Calibration of Fundamental Stellar Quantities*, ed. D.S. Hayes, L.E. Pasinetti & A.G.D. Philip, p. 225
Holweger, H. (1970) *A&A*, **4**, 11
Kurucz, R.L. (1979) *ApJS*, **40**, 1
Kurucz, R.L., Furenlid, I., Brault, J. and Testerman, J. (1984) *Solar Flux Atlas from 296 to 1300 nm*, National Solar Observatory, Sunspot, NM.

Kurucz, R.L. (1991) in *Stellar Atmospheres: Beyond Classical Models*, ed. L. Crivellari, I. Hubeny & D.G. Hummer, NATO ASI Series, Kluwer, Dordrecht, p. 408.
Kurucz, R.L. (1992a) in *The Stellar Populations of Galaxies*, ed. B.Barbuy & A. Renzini, Kluwer, Dordrecht, p. 225
Kurucz, R.L. (1992b) *Rev. Mex. Astr. Astrof.*, **23**, 181
Kurucz, R.L. (1993a) *CD-ROM 13, ATLAS9 Stellar Atmosphere Programs and 2 km/sec Grid*, Cambridge, Smithsonian Astrophysical Observatory
Kurucz, R.L. (1993b) *CD-ROM 18, SYNTHE Spectrum Synthesis Programs and Line Data*, Cambridge, Smithsonian Astrophysical Observatory
Labs, D. and Neckel, H. (1968) *Z.Astrophys*, **69**, 1
Labs, D. and Neckel, H. (1970) *Solar Phys*, **15**, 79
Lockwood, G.W., Tug, H. and White, N.M. (1992) *ApJ*, **390**, 668 (LTW)
Neckel, H. and Labs, D. (1984) *Solar Phys*, **90**, 245 (NL84)
Stevenson, C. C. (1994) *MNRAS* **267**, 904
Tripicco, M.J. and Bell, R.A. (1995) **AJ** (in press, Dec.)
Wishart, A.W. (1979) *MNRAS*, **187**, 59P

https://doi.org/10.1017/S0074180900083558 Published online by Cambridge University Press

Roger Bell (*right*) enjoying a little chat with Dan Kiselman.

Sorry, cookies are out! *From left to right:* M. Cuntz, V. Klückers, D. Dravins, K.-H. Hofmann, J. Baldwin.