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Observed versus predicted stellar flux distributions of solar-type stars

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Abstract
I have compared the low-resolution spectrophotometric fluxes in the visible spectral region of F- and G-type MARCS 2008 model atmospheres to six spectrophotometric databases of the Sun and stars. These observational databases disagree with each other concerning the overall red/blue flux balances on the several percent scale for the same objects. There is, however, no systematic overall trend between MARCS model fluxes and these observations taken together and therefore no reason to suspect any problem with the MARCS overall spectrum balance. The results strongly suggest, however, that there are systematic errors in the ultraviolet and blue opacities used in the construction of the model atmospheres. These errors appear in wavelength regions with widths of some 50–150 Å. Similar uncertainties are found also in other independent libraries of synthetic model atmosphere fluxes. I also highlight a number of unidentified spectral features with unusual shapes in spectra of the Sun and solar-type stars.

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1. Introduction

Stellar electromagnetic fluxes supply the most detailed information available from stars. A model of a particular stellar atmosphere should agree with the observed flux to a sufficient degree dependent on the particular application. In our work towards a new generation of one-dimensional (1D), hydrostatic and flux-constant MARCS local thermodynamic equilibrium (LTE) model atmospheres (Gustafsson *et al* 2008) very large amounts of opacity data of atoms, molecules and ions have been assembled and used. I here compare the resulting surface fluxes of models of solar-type stars in low resolution over the visible wavelength region with databases of solar and stellar observations. I also show some comparisons between different observed databases. A comparison of the fluxes of the MARCS solar model with those of other brands of solar model atmospheres is also presented. All comparisons are made using flux data binned into 50 Å wavelength intervals. This resolution is of interest particularly for the interpretation of photometric data.

Within the present limitations in available computer power, one has to use geometrically simple 1D hydrostatic model atmospheres to compare in detail the very large amounts of opacity data necessary to describe the radiative energy transport in stellar photospheres with observations.

2. Comparison with observed solar fluxes

2.1. Observed solar fluxes

Neckel and Labs (1984) may be the most well-known work on the total solar irradiance as observed from the ground. A correction to that data, based on revised disc-centre continuum intensities and limb-darkening functions, was presented by Neckel (2003). The correction was also guided by a comparison with the more recent and independent flux calibration presented by Burlov-Vasiljev *et al* (1995). The two datasets are compared in figure 1.

Thuillier *et al* (2004) assembled the composite solar irradiance spectrum from various space-based observations and spectrometers. These are compared with those of Burlov-Vasiljev *et al* (1995) in figure 2.

The two figures show that the agreement between the different datasets is not impressive: the relative flux differences reach several per cent. It is therefore difficult to know with which dataset the model fluxes should agree. The space-based data sugggest the ‘reddest’ colours, while those of Burlov-Vasiljev *et al* are the ‘bluest’ with Neckel and Labs falling in between. Simply because of its more extensive wavelength coverage I will use the data of Thuillier *et al* (2004) for the following comparisons.

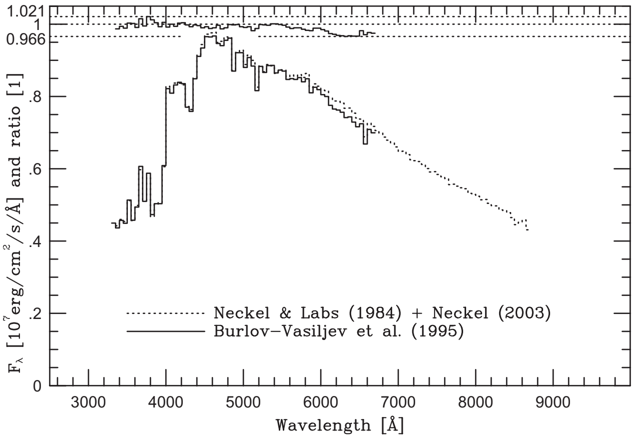

Figure 1. The disc-integrated absolute solar flux according to Burlov-Vasiljev *et al* (1995) and Neckel and Labs (1984) corrected according to Neckel (2003). On top is the ratio of Burlov-Vasiljev *et al* to the latter.

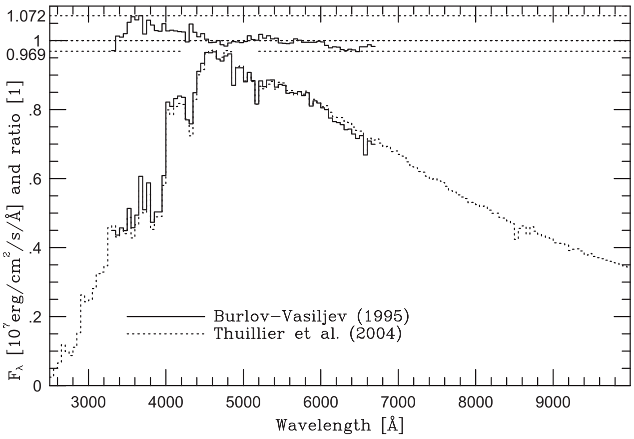

Figure 2. The disc-integrated absolute solar flux according to Burlov-Vasiljev *et al* (1995) and Thuillier *et al* (2004). On top is the ratio of Burlov-Vasiljev *et al* to Thuillier *et al*.

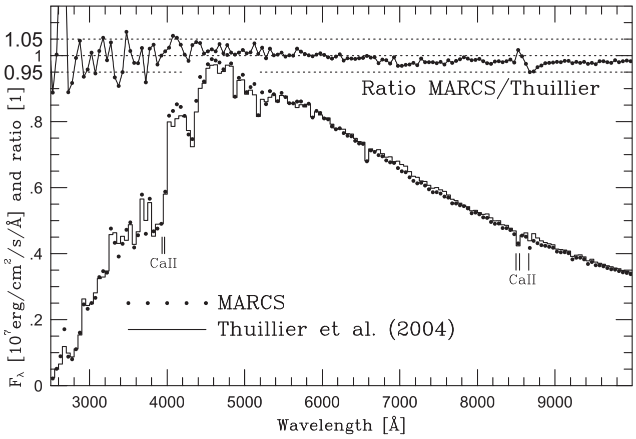

Figure 3. Comparison of the absolute fluxes of the MARCS (Gustafsson *et al* 2008) solar model to the space-based data of Thuillier *et al* (2004). The ratios MARCS/observations are shown at the top of the figure.

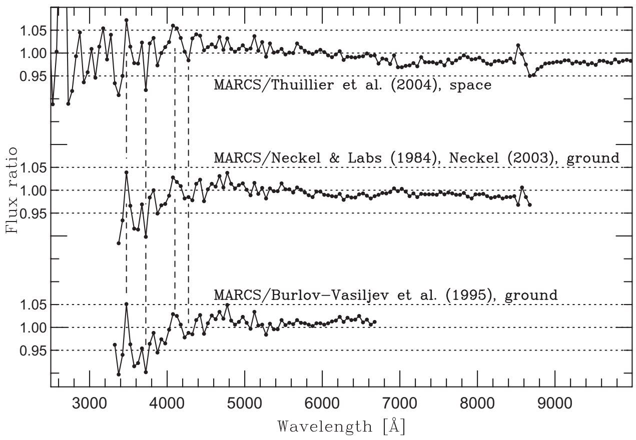

Figure 4. The MARCS solar flux ratioed to three sets of observations. The vertical dashed lines exemplify the persistent pattern of peaks and valleys below 4500 Å seen in all three comparisons.

2.2. The MARCS solar flux

The MARCS models are computed with opacities tabulated in 10^5 wavelength points sampled with a uniform 'resolving power' of $R = \lambda/\delta\lambda = 20\,000$. The surface fluxes at these wavelengths are computed when the model has converged and are supplied on the MARCS web pages at http://marcs.astro.uu.se/ together with the model structures and other physical parameters. This sampling is not dense enough to sample all spectral lines, which is why there is a statistical uncertainty in the model fluxes summed over a limited wavelength range. Based on numerical experiments we estimate the standard deviation of this 'sampling noise' to be about 3% in 50 Å intervals in the 2500–4000 Å region where it is the largest and where the line-depth contrast is the highest for solar-type stars. Redwards of 6500 Å the corresponding noise is 0.5% and in the intermediate region it falls off fairly linearly. In figure 3, the MARCS solar model fluxes ($T_{\rm eff} = 5777$ K and $\log g = 4.44$ (cgs), [Fe/H]$\equiv$ 0.00, and microturbulence parameter $\xi_t = 1.0\,{\rm km\,s^{-1}}$) are compared with the observations presented by Thuillier *et al* (2004). The 'transient' in the flux ratio seen around 8600 Å is likely due to problems in the merging of observational data from two different spectrographs and space missions (SOSP at Atlas and SOLSPEC at Eureca). The flux comparison is here furthermore complicated by the fact that the region also contains the strong Ca II infrared-triplet lines and the hydrogen Paschen discontinuity. A meaningful comparison can therefore not be made in this region, cf also section 2.3.

Figure 4 shows the ratio of MARCS to the three observed solar flux distributions. Although the three observed datasets have different blue/red spectral balances, the consistent positions of peaks and troughs below 4500 Å (examples are indicated by the dashed vertical lines) suggest that these are likely to be artefacts of errors in the model fluxes and opacities. Our estimated model 'sampling noise' for single 50 Å intervals (see above) cannot explain these features.

2.3. Other solar model fluxes

It is interesting to compare the MARCS solar fluxes also to those of other solar photospheric models. In figure 5, the 50 Å binned absolute fluxes of other solar models are compared with the observations of Thuillier *et al* (2004). At the top, the model fluxes are those presented by Heiter *et al* (2002) which were based on ATLAS9 models and opacities of R L Kurucz (http://kurucz.harvard.edu/grids.html). The second

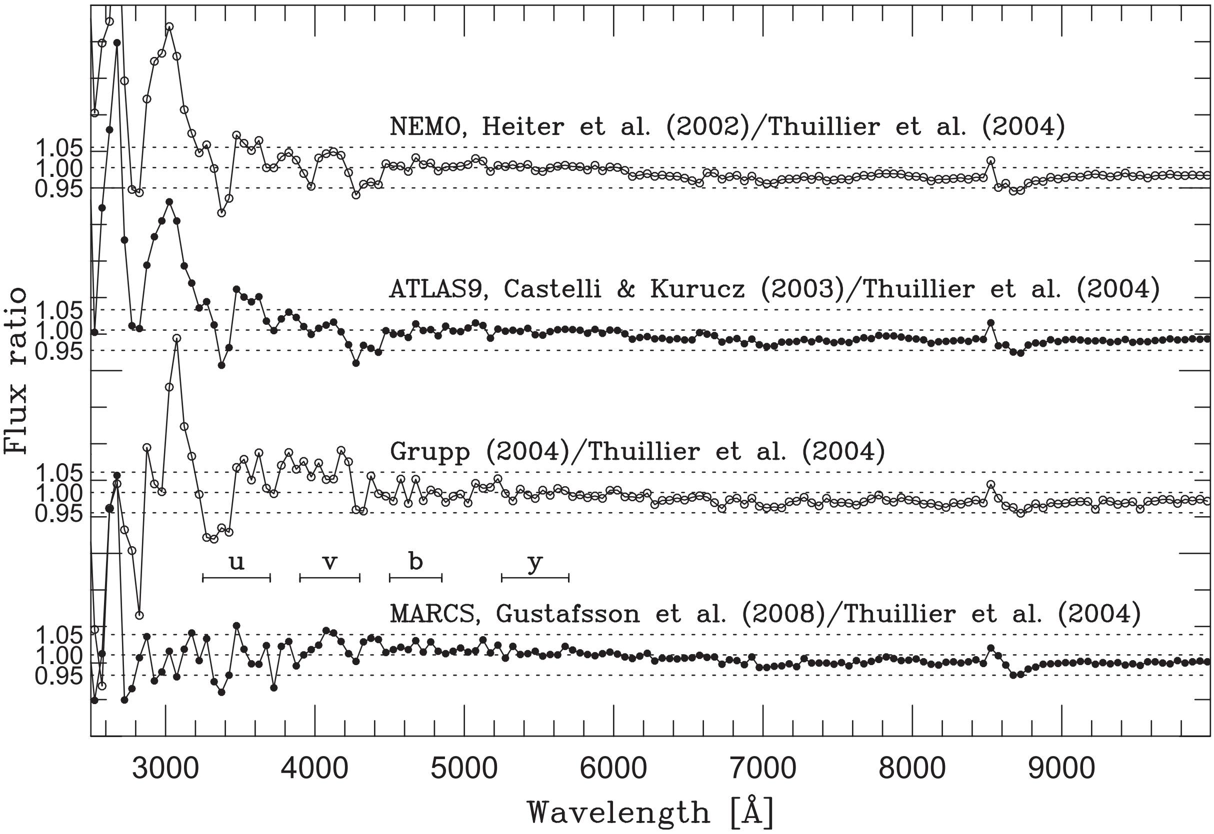

Figure 5. Solar photospheric model fluxes compared with observations. The dominating portions of the Strömgren *uvby* photometric passbands are also indicated.

comparison is also based on Kurucz's ATLAS9 model code, however, with updated opacities as presented by Castelli and Kurucz (2003). The third line is data from Grupp (2004) and the fourth flux distribution ratio is that of MARCS presented in figure 3.

There are similarities and differences between the different model fluxes. They all show the problem with the observed fluxes around 8600 Å noted above. All the model fluxes are also systematically lower than the observations redwards of ≈6000 Å. This may be due to a calibration error in these particular observations since they were found to be redder than the two other solar irradiance datasets in section 2. All four model datasets show a local dip at the G band around 4300 Å in comparison with neighbouring regions. An even stronger dip around 3400 Å seems to be present in all four model fluxes, possibly due to an exaggerated band of the NH molecule. At even shorter wavelengths, the MARCS fluxes seem to be generally more well behaved than the other data sets. There is, however, a very pronounced flux leak of about 40% in MARCS (and apparently with an even larger amplitude also in the two ATLAS9 data sets) between approximately 2640 and 2700 Å. Since a very low fraction of the solar flux is carried in this wavelength range, this problem has a negligible effect on the LTE model structure.

2.4. Comparison with observed stellar fluxes

There are a number of spectrophotometric databases of stars. I will compare MARCS model fluxes with three of these. All three are ground based, supply de-reddened fluxes and estimates of fundamental parameters. Like for the solar comparisons, the data has been binned in 50 Å intervals for the comparisons.

The first database in this comparison is STELIB, assembled by Le Borgne *et al* (2003) and available at http://webast.ast.obs-mip.fr/stelib/. It uses data from the Jacobus Kaptein Telescope at La Palma with the Richardson–Brealey spectrograph and the 2.3 m telescope at Siding Spring Observatory with its Double Beam Spectrograph. The spectra cover the wavelength range 3200–9900 Å and have a resolution of 3 Å, giving a wavelength-dependent resolving power between 1100 and 3300. The spectra are de-reddened, i.e. corrected for interstellar extinction and flux calibrated relative to UBVRI standard stars.

Out of the 249 stars in the STELIB database, only those with a complete observed wavelength coverage and with parameters within the limits of the current MARCS database were used for the comparison except for a few stars with obviously erroneous parameters or spectra. The MARCS range is $T_{\rm eff}$ 4000 to 8000 K, $\log g$ 0.0 to 5.0, [Fe/H] −5.0 to +1.0. The selection resulted in 93 stars for the comparison. The standard (Galactic disc) sequence of [α/Fe] was chosen and microturbulence parameters 1.0 km s^{-1} for $\log g \geqslant +3.5$ and 2.0 km s^{-1} for lower surface gravities (http://marcs.astro.uu.se/). In figure 6, the ratios of MARCS library fluxes, linearly interpolated in $T_{\rm eff}$, $\log g$, and [Fe/H] relative to the STELIB observed fluxes are shown. Both the model fluxes and the observed fluxes were first renormalized such that the average flux in the interval 4750–5750 Å is

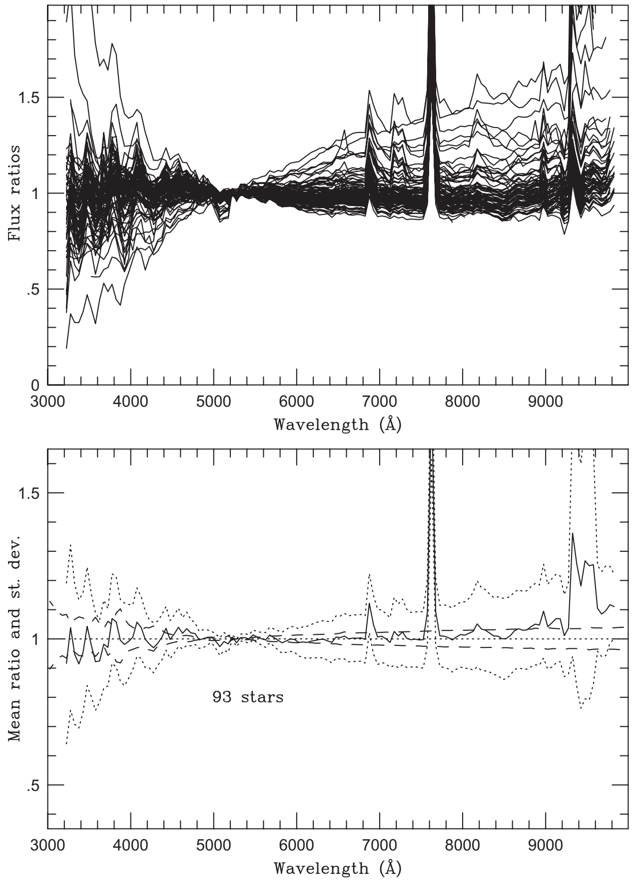

Figure 6. Upper panel: the ratios of MARCS model fluxes to those of 93 stars in the STELIB database. Lower panel: the solid line and the two dotted lines show the mean value and ± the standard deviations of the ratios in the upper panel. The dashed lines show the typical effects of effective-temperature changes of ±100 K.

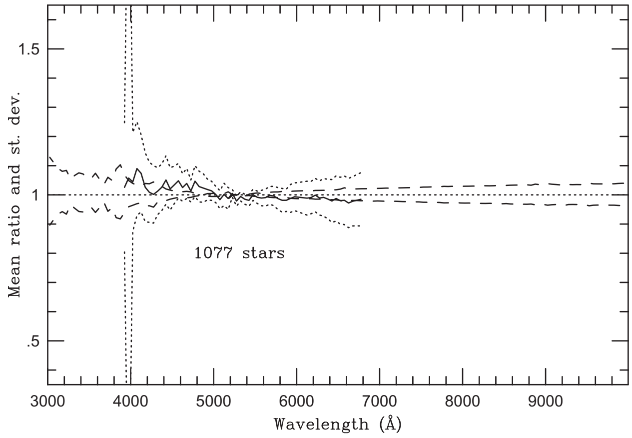

Figure 7. The solid line and the two dotted lines show the mean value and standard deviations of the ratios of MARCS fluxes to the observations in ELODIE.3.1. The dashed lines show the typical effects of effective-temperature changes of ±100 K.

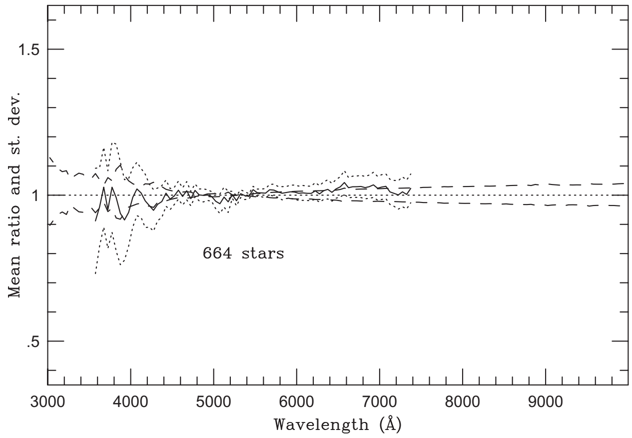

Figure 8. The mean ratio and standard deviations of MARCS model fluxes to those of 664 stars in the MILES database. The dashed lines show the typical effects of effective-temperature changes of ±100 K. The scatter is considerably smaller than for the other two databases.

1.0 for all spectra. In the upper panel, 93 flux ratios are plotted and the lower panel shows the average ratio (solid) and the standard deviations (dotted). The effects on the observed spectra by Earth's atmospheric absorption bands of O_2 and H_2O are obvious and make the comparison less useful beyond about 6800 Å. It appears that the MARCS fluxes with the STELIB stellar model parameters have on average the same overall slope as the observed spectra. The two long-dashed lines show the effect of effective-temperature changes of ±100 K for a solar-type star. The large scatter (dotted lines) then suggests that the precision in the STELIB stellar parameters, fluxes, and reddening corrections correspond to stochastic effective temperature errors of between 200 and 300 K for solar-type stars.

ELODIE.3.1 (Prugniel *et al* 2007) presents spectrophotometric data with $R \approx 10\,000$ between 3900 and 6800 Å for 1388 stars. The observations were made with the Observatoire de Haut-Provence 1.93 m telescope and the ELODIE fibre-coupled echelle spectrograph. The spectra are corrected for interstellar reddening. The flux normalization was made using Tycho B and V photometry (Scales *et al* 1992). ELODIE.3.1 claims a photometric precision of 2.5%.

Like for the STELIB data, all good ELODIE stars with sufficient observed wavelength coverage and with parameters within the limits of the current MARCS database were used for the comparison. Figure 7 shows the average ratio MARCS/ELODIE (solid) and the standard deviations relative to the mean of an individual ratio (dotted). The two long-dashed lines show the typical effects of effective-temperature changes of ±100 K for a solar-type star. A comparison between the dotted and dashed lines suggests that the ELODIE broad-band fluxes and effective temperatures together give a scatter of more than 200 K. It can also be seen that the MARCS fluxes typically display approximately 100 K 'bluer' spectra than the ELODIE stellar parameters suggest.

The third spectrophotometric database is called MILES (Sánchez-Blázquez *et al* 2006). It contains data for 985 stars and the observations are medium-resolution spectra from the Isaac Newton Telescope at La Palma. Atmospheric absorption by O_2 and H_2O has been divided out and the flux calibration was made by observations of five spectrophotometric standard stars and reddening corrections have been applied. The 664 spectra used here cover the wavelength range 3550–7400 Å and the spectral resolution is 2.3 Å which gives a wavelength-dependent resolving power varying from 1500 to 3200. The MILES stellar fundamental parameters are given by Cenarro *et al* (2007). Figure 8 shows

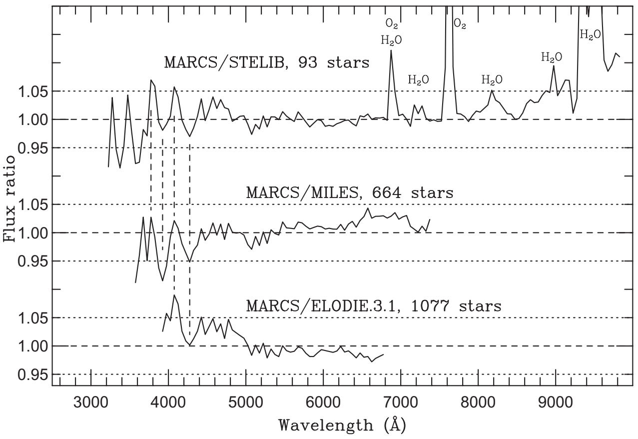

Figure 9. The mean ratios of MARCS model fluxes to three independent stellar spectrophotometric databases. The vertical dashed lines serve to guide the eye to the most obvious features in the ratios that seem to be in common for the three comparisons.

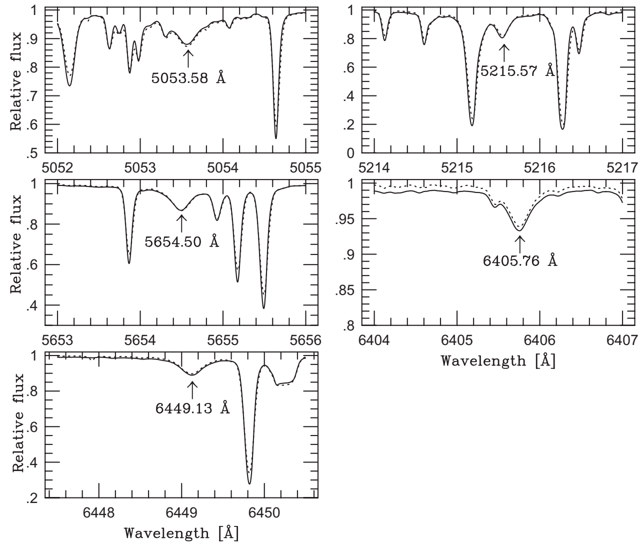

Figure 10. The unidentified lines in the solar spectrum. The dotted line is the solar integrated flux atlas of Kurucz *et al* (1984) and the solid line is the disk centre intensity spectrum of Delbouille *et al* (1973). The line wavelengths are those given by Moore *et al* (1984).

the average ratio MARCS/MILES (solid) and the standard deviations (dotted). The two long-dashed lines show the effects of T_{eff} changes of ±100 K for a solar-type star. The standard deviations of the MARCS/MILES flux ratios are seen to be considerably smaller than for the STELIB and ELODIE databases, about 150 K, and the MARCS spectra typically appear to show overall slopes about 100 K 'redder' than the MILES spectra. It was noted by Sánchez-Blázquez *et al* (2006) that the MILES flux calibration is systematically 'bluer' than that of other spectrophotometric databases. This is also obvious when spectra of stars in common with other spectrophotometric databases are compared.

A comparison with the three independent observational data sets is shown in figure 9. Just as for the comparison with solar data these three average ratios show different slopes and a distinctive likeness between peaks and troughs in the blue. A comparison with figure 4 confirms that the main features are the same as were found from the solar comparisons. This strengthens the suspicion that the MARCS model atmosphere fluxes and opacities suffer from errors on the order of several per cent in particular bands in the blue and near-ultraviolet spectral region with characteristic widths of between 50 and 150 Å.

3. Some interesting unidentified lines in the solar spectrum

During my work with astrophysical values of $\log gf$ for MARCS in 1998, a number of spectral lines with unusual shapes and without correspondence in available atomic or molecular line databases were noticed. These are (i) rather shallow, (ii) unusually wide and (iii) have unusually round line bottoms. The three clearest examples have line centres near 5053.58, 5654.50 and 6449.13 Å. Moore *et al* (1966) give their equivalent widths in the disc-centre solar spectrum as 50, 75 and 34 mÅ respectively. Two further less certain cases are found at 5215.57 and 6405.76 Å with equivalent widths given by Moore *et al* as 26 and 13 mÅ, respectively. The lines in the solar intensity and integrated spectra are shown in figure 10.

Moore *et al* comment on how lines behave in sunspots: 5053.58 Å receives no comment, 5654.50 has an unchanged strength and is noted to be 'diffuse'. The line at 6449.13 Å is noted to be 'strengthened', 'diffuse' and 'double', and in a note 'Blend of a molecular and an atomic line in the sun-spot spectrum' (the lines are not identified, however). The 5215.57 Å line is 'weakened' and receives a note: 'Possibly a molecular line in the sun spot spectrum'. The 6405.76 Å line is 'unchanged ?' and 'very diffuse' in the sun spot spectrum.

I have tried to identify these lines, but so far without success. One possibility is that they are simply blends of normal unidentified lines which happen to result in symmetric features. Another possibility is that they may be autoionizing lines, however, without showing the characteristic asymmetric Fano profiles. They may also be magnetically sensitive, in particular the lines at 5654.50, 6449.13 and 6405.76 Å which are noted by Moore *et al* to be 'diffuse' or 'very diffuse' in sun spot spectra. Perhaps certain autoionizing lines may be sensitive to effects of magnetic broadening.

I have inspected a number of spectra in the VLT high-resolution spectroscopic database UVES Paranal Observatory Project (UVES POP, Bagnulo *et al* (2003)), and find that these features are seen with similar properties also in the spectra of other solar-type stars. The features become stronger in cooler stars and weaker in metal-poor ones, as one would expect for most neutral atomic or molecular lines.

4. Conclusions

I have compared the broad-band fluxes in the visible spectral region of F- and G-type MARCS 2008 model atmospheres (Gustafsson *et al* 2008) to six spectrophotometric databases of the Sun and stars. The fluxes of these databases disagree with each other on a scale of several per cent for the same stars. The flux ratios of MARCS models to the whole ensemble of data sets show no systematic trend in the overall blue/red balance. In all six instances, however, a consistent pattern of valleys and mounds in the fluxes below about 4500 Å with widths of about 50–150 Å and amplitudes of up to at least 7% (considerably larger than the estimated statistical effects of the model-flux sampling) can be seen in the ratios. This strongly indicates that there are systematic uncertainties in the opacities used in the construction of the model atmospheres. The nature of these deficiencies will be further investigated.

Larger uncertainties of a similar nature are found also in other independent libraries of synthetic model atmosphere fluxes.

This work will be further elaborated in a forthcoming paper on the MARCS F- and G-type photospheric models.

A number of unidentified spectral features with an unusual shape in the spectra of the Sun and solar-type stars have been highlighted.

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Appendix. Discussion

Q: (Bob Kurucz) I compute the whole spectrum and make the comparisons at 1 Å per page with line identifications. I will begin putting these plots on my website. Half the lines are missing from the line lists. The solution is to improve the laboratory analysis and to fill out the atoms with semi-empirical calculations that will produce the missing lines. I am making those calculations.

Q: (Andreas Korn) The differences in observed solar fluxes are truly disturbing. Which experiment will sort this out?

A: Yes, the errors from synthetic photometry are several tenths of a magnitude in the blue-UV. We have to continue our testing of opacities by comparison to absolute solar fluxes and stellar fluxes and ask theoreticians and experimenters for improved line- and continuum-opacity data. Also the spectra from future 3D NLTE MHD simulations will be wrong if the opacity data is wrong. The present-day uncertainties in gf values and cross-sections are large enough that considerable progress can be made with simple 1D LTE model atmospheres where high resolution is possible.

Q: (Ulrike Heiter) For the comparison of MARCS model fluxes with spectra from empirical libraries, which parameters did you take as input for the models?

A: Those given in the libraries by the respective authors.

Q: Then the comparison rather tells you about the relation of MARCS models to the calibration of parameters used by the different libraries.

A: No, only to a small extent. When we compare the observed fluxes of stars in common between the data sets we see the same differences (more or less). There are no large systematic differences between the parameters derived by the different authors.

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