3D Stellar atmospheres
ASP Conference Series, Vol. 210th IAU Symposium, 2002
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Radiative Transfer with very Few Wavelengths

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Abstract. Our aim is to develop an opacity sampling scheme suitable for 3D hydrodynamical simulations of convective stellar atmospheres. This paper presents a feasibility test for the concept.

1. Introduction

3D hydrodynamical simulations of convection near stellar surfaces are largely governed by the interplay between radiation- and hydro-dynamics. A treatment of radiation that accounts for the full effect of line-blanketing is therefore necessary. So far we have included line-blanketing through a *opacity binning* method, as detailed in Sect. 2.

Solar simulations show good agreement with line-profiles and bi-sectors, without the need for the usual macro- and micro-turbulence parameters (Asplund et al. 2000). Also the use of a horizontally- and temporally-averaged simulations, matched with a 1D solar model, greatly improves the agreement with observed high-degree p-modes (Rosenthal et al. 1999). There is also at least a superficial agreement with the granulation structure, although a more quantitative analysis has yet to be carried out. Simple Fourier-analysis is not adequate, as shown by Nordlund et al. (1997).

There is, however, still some disagreement with limb-darkening data, hydrogen Balmer-line profiles and the cores of strong lines. We also see a little too much flux in the ultra-violet. These problems have prompted us to look into improvements to the scheme for solving the radiative transfer.

2. Primer on Opacity Binning

Currently the simulations employ an Opacity Binning scheme, relying on a monochromatic, forward calculation performed on the average structure of the simulation. This method resembles opacity distribution functions (ODFs) and like ODFs, can include the statistics of large number of actual wavelengths in a number of bins, orders of magnitude smaller.

The opacity binning is performed as follows: 1) The bin membership of a wavelength is decided by the opacity, $\kappa_\lambda(\varrho, T)$, at the point in the 1D atmosphere where the monochromatic optical depth reaches unity. 2) The (pseudo) source-function of each bin, is the sum of the Planck-function at all wavelengths in that bin. 3) For the opacity, we use the Rosseland opacity of the continuum-bin in the optical deep case, and interpolate to the intensity weighted average opacity for $\tau \rightarrow 0$. 4) The opacity bins are equidistant in $\log\kappa$ and the opacity of each bin is assumed likewise equidistant. These (pseudo) source-functions and the interpolated opacity are then used in the 3D simulations. For each angle, the radiative transfer is thus solved $N_{\rm bin}$ times; we typically use $N_{\rm bin} = 4$.

3. Primer on Opacity Sampling

Opacity sampling (OS) consists of performing monochromatic radiative transfer for a large number of random wavelengths. It is a statistical method because of the random selection of wavelengths (in practice, equally spaced in, e.g., $\log\lambda$). Because of the extremely complicated behavior of stellar opacities, more than 10^4 wavelengths are needed before the procedure converges. For K and M stars, the number may be significantly larger to capture the statistics of all the thin molecular lines, whereas hotter and metal-poor stars can do with less. Full OS is therefore prohibitively expensive for 3D hydrodynamical simulations.

4. How to reduce the problem

We do have the computer-power to perform radiative transfer of the order of 50 wavelengths. If we abandon the statistical nature of OS and carefully select those wavelengths, we might get something close to the monochromatic result.

We calculate normal MARCS stellar atmospheres (Asplund et al. 1997) with $N_\lambda \approx 10^5$ and use those as a test-bed for our method, which we call selective opacity sampling (SOS). So how do we choose the 50 wavelengths out of a set of 10^5?

1. We split the whole spectrum up into $N_{\rm regions} = 10$ regions.
2. Group (bin) the wavelengths of each region, according to morphology - e.g. position of the minimum of the heating, $q(\tau)$. We use $N_{\rm bin} = 5$.
3. Find the average $q(\tau), J(\tau), H(\tau)$ and $K(\tau)$ of each bin.
4. Find the one wavelength from each bin, that best reproduce these averages.
5. The two bins with most members are subjected to 2D minimization procedure, to find out which pair of wavelengths from those two bins will reproduce the remaining radiative transfer in that region.
6. Finally the (positive definite) weights of all $N_{\rm regions}N_{\rm bin} = 50$ wavelengths are χ^2-optimized to give the best fit to the total $q(\tau), J(\tau), H(\tau)$ and $K(\tau)$.

5. Results

We have carried out this wavelength selection procedure on a number of MARCS models, as shown in Fig. 1. The atmosphere parameters are listed at the top

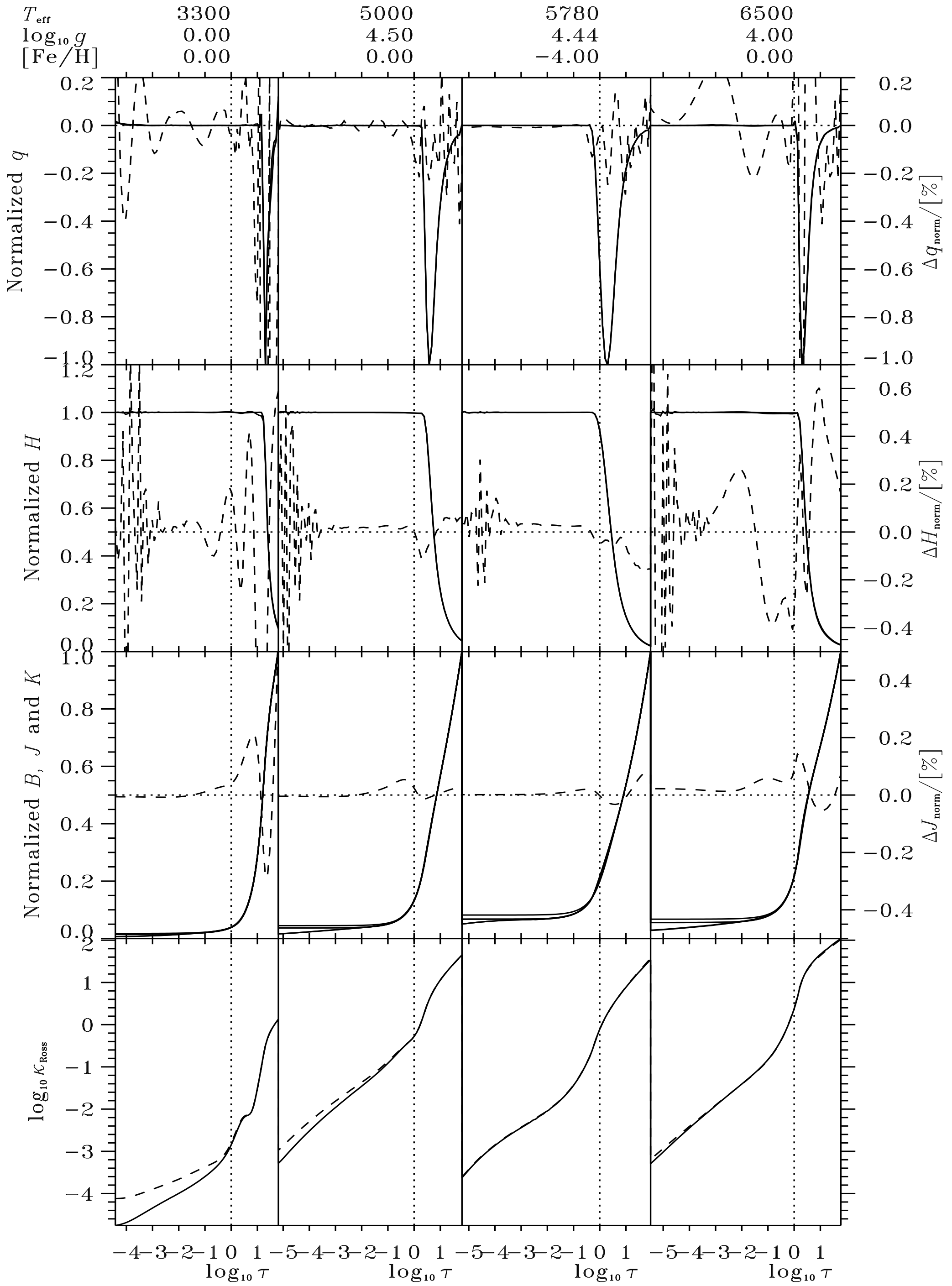

Figure 1. Heating q, flux H, J, B, $3K$ and Rosseland opacity for four of the test cases (horizontally). In the three upper panels, the dashed line (right axis) is the differences in the sense SOS − monochromatic. In the lower panel the dashed line is the Rosseland opacity from our method. The horizontal dotted lines are the zero-points for the differences, and the vertical ones show the location of $\tau = 1$.

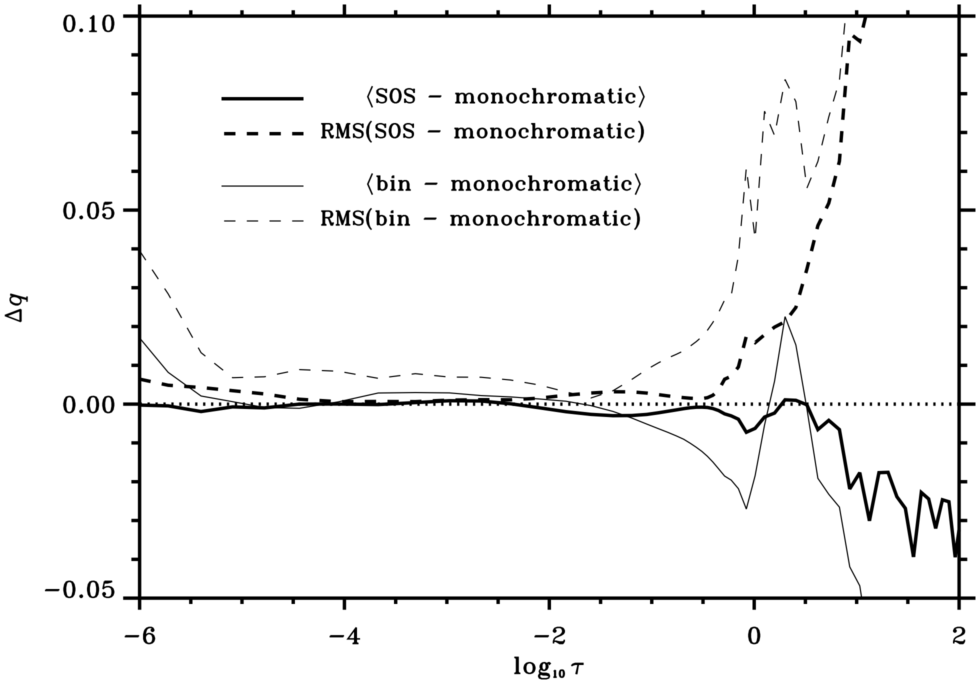

Figure 2. Comparison of the heating from the opacity binning (bin - thin lines) and our new method (SOS - thick lines), with the "monochromatic" case (see text). A $\langle\ldots\rangle$ denotes averages over a $1.5{\times}6$ Mm, $82{\times}200$ point vertical slice from a solar simulation (solid). RMS denotes the corresponding root-mean-squares (dashed).

of the plot. We have plotted both the full 10^5 wavelength MARCS results and our corresponding results with just 50 wavelengths, but the differences are only immediately visible in $\kappa_{\rm Ross}$ for which we did not fit. For the other quantities we also plotted the differences (dashed lines, right hand axis). The photospheric dip in the heating, q, arise from the transition from convective to radiative transport of the flux. In the second plot from the bottom, 3K is larger than B, which is larger than J, only diverging above the photosphere. In this plot we only plot the J-differences, which is representative of the B- and K-differences too. We see that our method is successful in reproducing the full radiation field to within a percent. The metal-poor atmosphere is easiest reproduced with few wavelengths, whereas the red giant (left) causes more problems due to the many molecular lines.

In Fig. 2 we test the old and the new method on a vertical slice of a solar simulation. We plot deviations from the "monochromatic" calculation, averaged over the horizontal dimension of the slice. Solid and dashed lines denote plain- and RMS-averages respectively, and the old opacity binning is shown with thin lines, and the new SOS method is shown with thick lines. The reference ("monochromatic") model in this case is based on the ODFs used in the ATLAS atmosphere-models of Kurucz (1992), with 230 ODFs of 12 points, corresponding to 2760 "wavelength"-points. This is a far smaller set of wavelengths to choose from, and the fit for the 1D average of the slice is about 10 times worse than what we saw in Fig. 1 for the MARCS models (Note that this does not say anything about the accuracy of MARCS or ATLAS models). In the future, the plan is to base our wavelength selection on a OS calculation for the 1D average stratification of the simulation with 10^5 wavelengths, but for now, we can test our new method on the ODF case. The accuracy should increase with more choices of wavelengths.

From Fig. 2 we see that our wavelength selection is more stable against convective fluctuations than the opacity binning method. Some of that is due to our new method explicitly fitting for q of the average structure, whereas the opacity binning is a forward calculation, with no feed-back mechanisms (i.e., an itterative fitting scheme). We see that both the average- and the RMS-deviations over the slice are smaller with our new method. We note in particular, that with the opacity binning there is a small systematic outward shift of the transition from convection to radiation. This is not present in the results of our new method.

6. Conclusion

This first feasibility analysis has shown that

1. It is indeed possible to find 50 wavelengths that can represent the radiative transfer of a full OS calculation with 10^5 wavelengths.
2. Both the heating and the first three moments of the intensity J, H, K are well reproduced.
3. Although the Rosseland opacity does not enter in our fitting criteria, it is reproduced to within 1% in the optical deep layers.
4. The proposed selective opacity sampling method is more stable against the convective fluctuations than the opacity binning.

References

Asplund, M., Gustafsson, B., Kiselman, D. & Eriksson, K. 1997, A&A, 318, 521

Asplund, M., Nordlund, Å., Trampedach, R., Allende Prieto, C., & Stein, R. F. 2000, A&A, 359, 729

Kurucz, R. L. 1992 in The stellar population of galaxies, ed. Barbuy, B. & Renzini, A., 225

Nordlund, Å., Spruit, H. C., Ludwig, H.-G. & Trampedach, R. 1997, A&A, 328, 229

Rosenthal, C., Christensen-Dalsgaard, J., Nordlund, Å., Stein, R. F. & Trampedach, R. 1999, A&A, 351, 689