The opacity pipeline: from atomic data to realistic RMHD simulations

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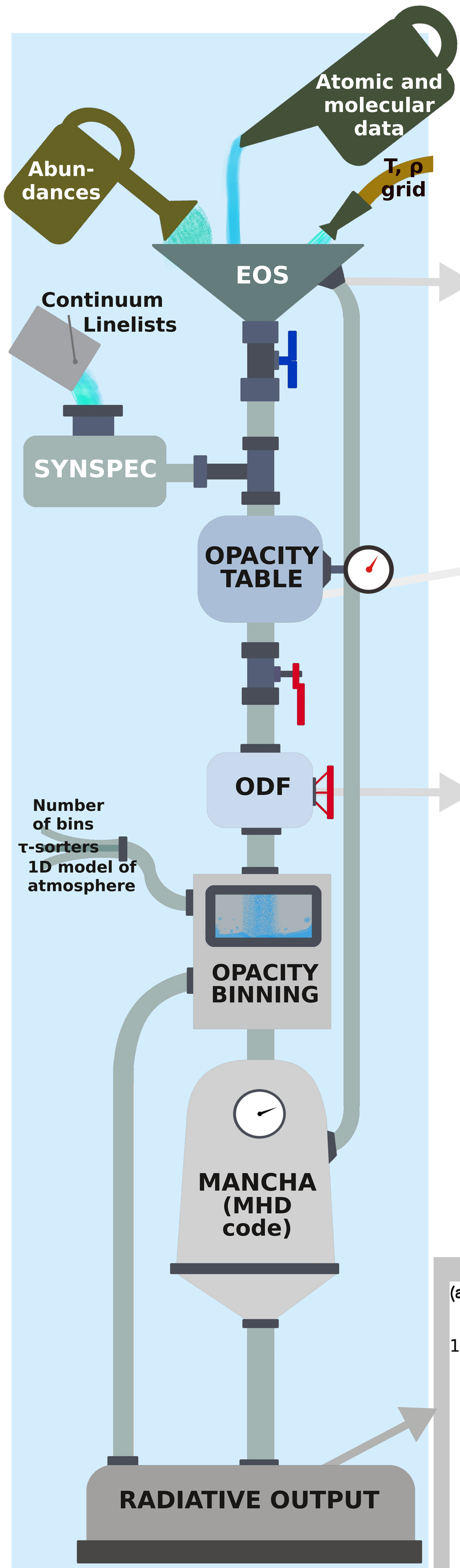
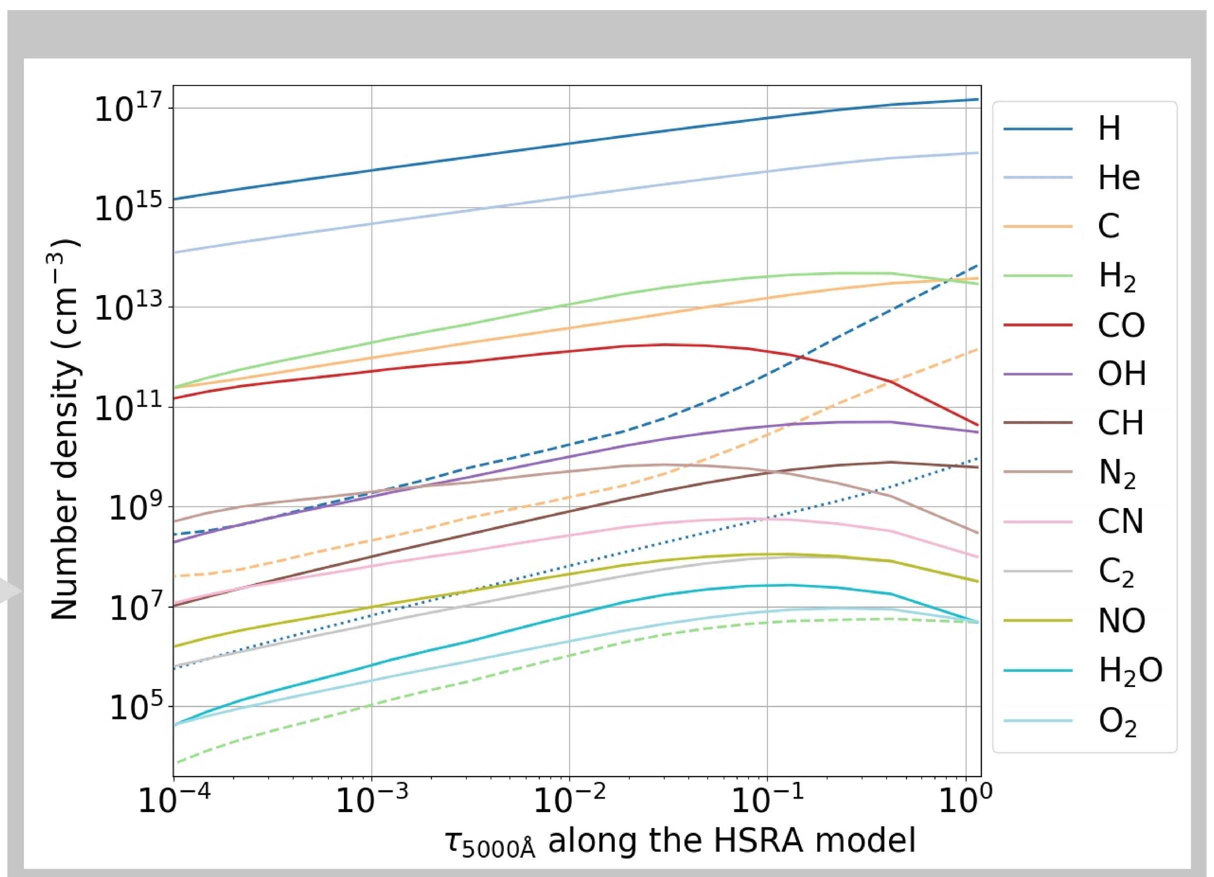
Introduction

We have developed a pipeline to produce the opacity bins needed in order to use the MANCHA code [1] to run convection simulations of cool stars beyond the solar case. The pipeline starts with the computation of opacity tables using the Synspec code [2]. This code's calculations for the equation of state (EOS) are consistent with our own EOS code, CHEOS. Then, we transform this opacity table into opacity distribution functions (ODF), tacking the same steps and sub-steps used to produce ATLAS's tables [3]. Finally, we perform the opacity binning (details on this procedure can be found in [4]).

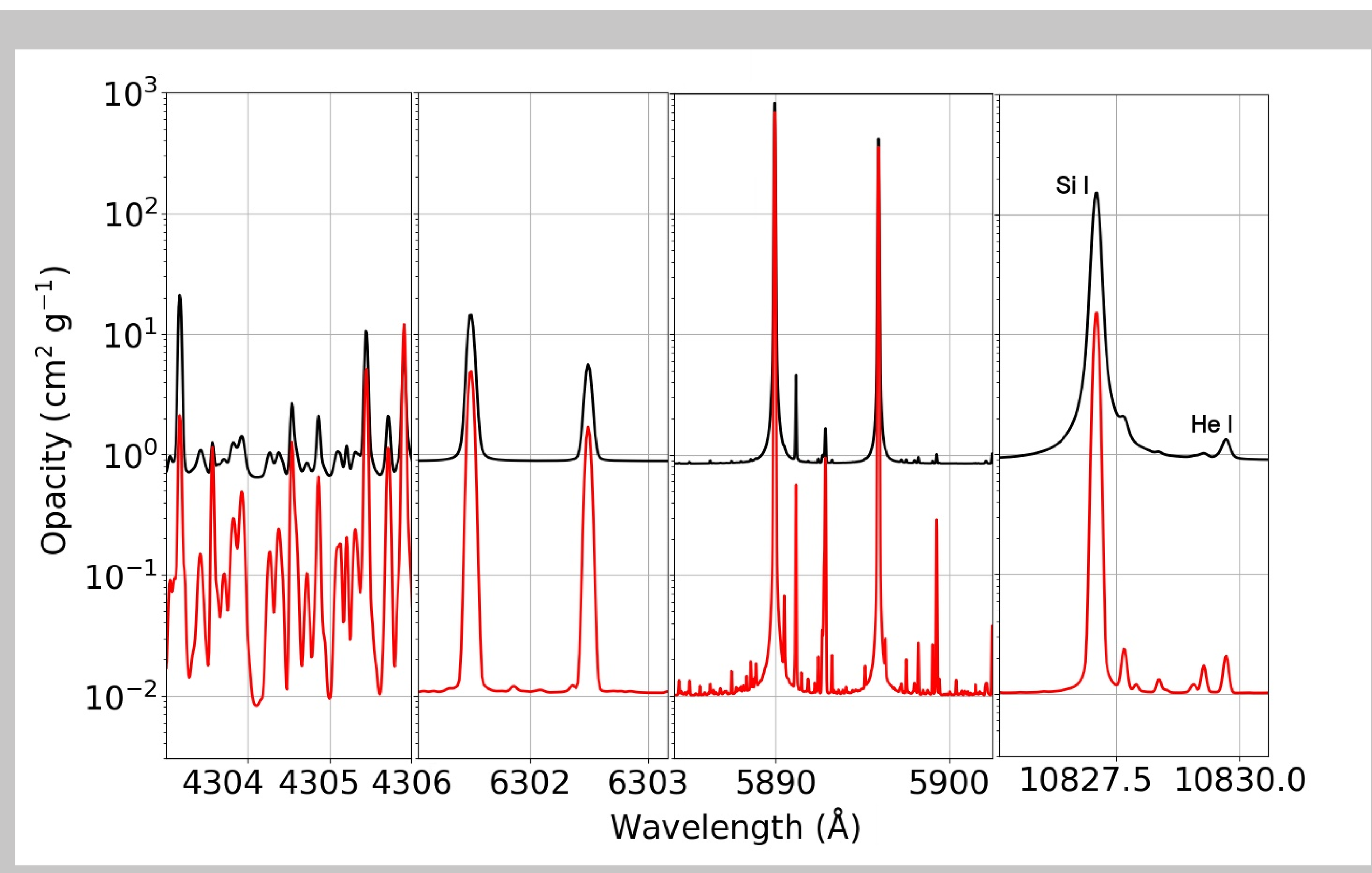
We present here the results of the pipeline for an opacity table suitable for the solar atmosphere. We also show the radiative outputs of solar RMHD simulations.

We plan to generate and use these tables for regimes of other cool stars.

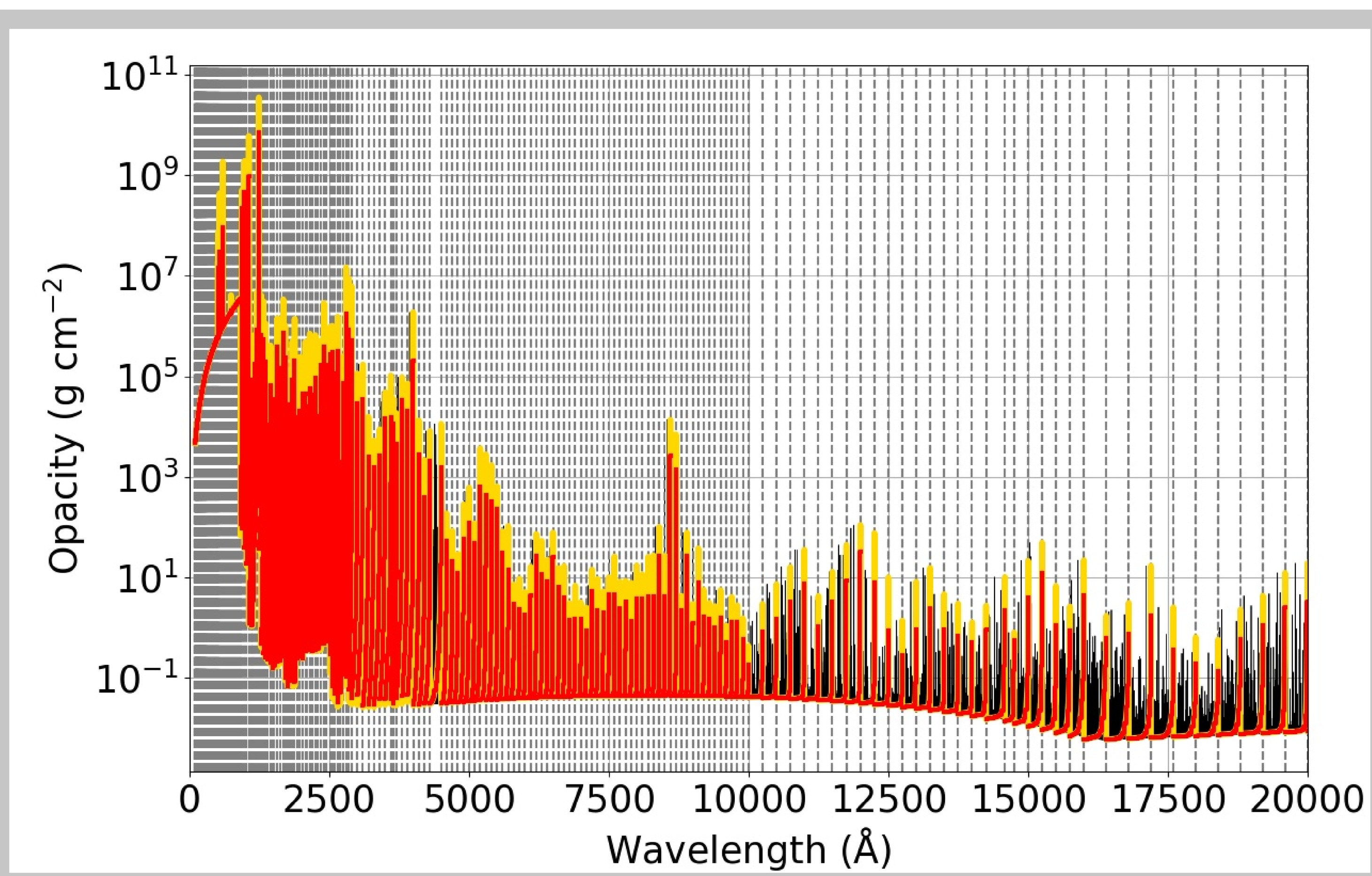


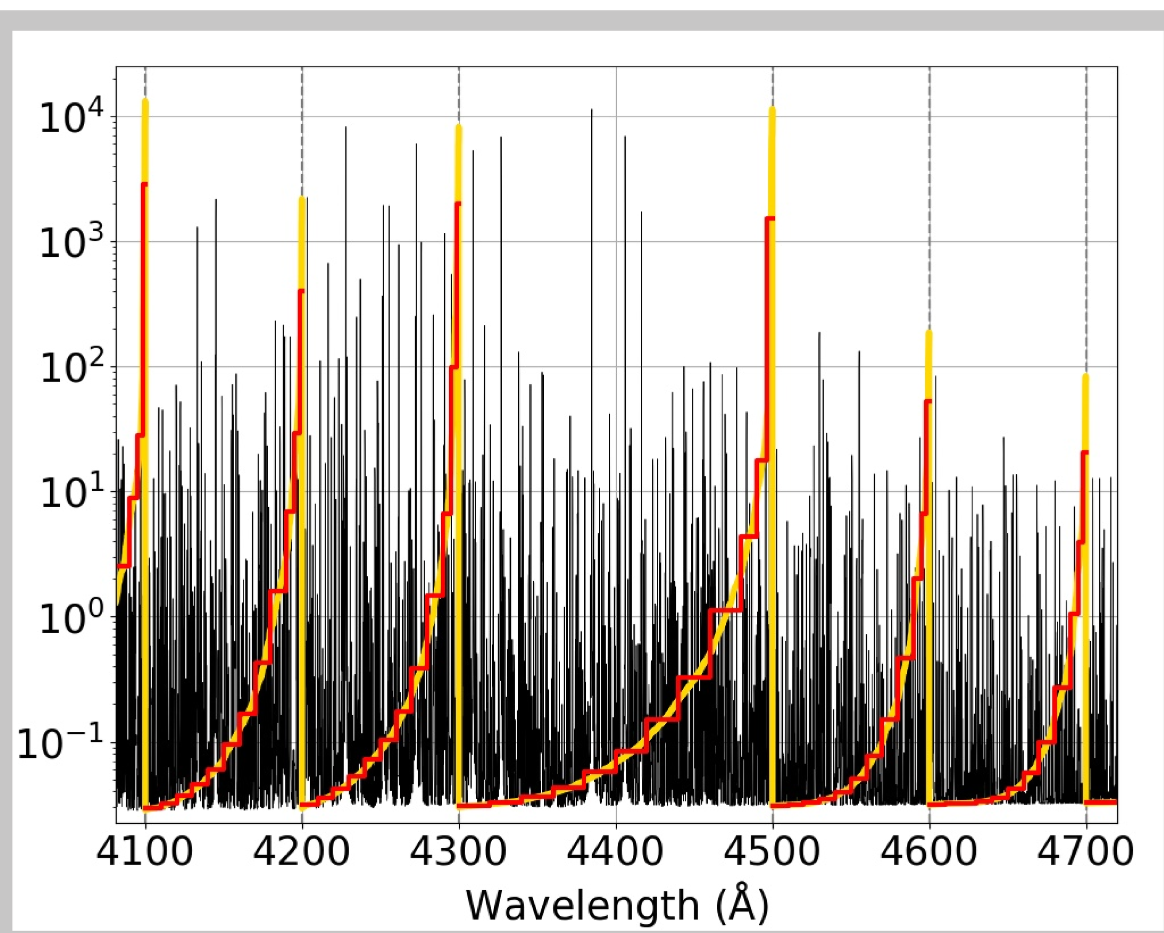


Number densities of different molecules and atomic species along the HSRA model atmosphere [5] from the optical depth at 5000 Å $\log_{10}\tau$=1.4 till $\log_{10}\tau$=-4 computed with CHEOS.
Solid line: neutrals; dashed line: single ionized; dotted line: negative hydrogen ion.

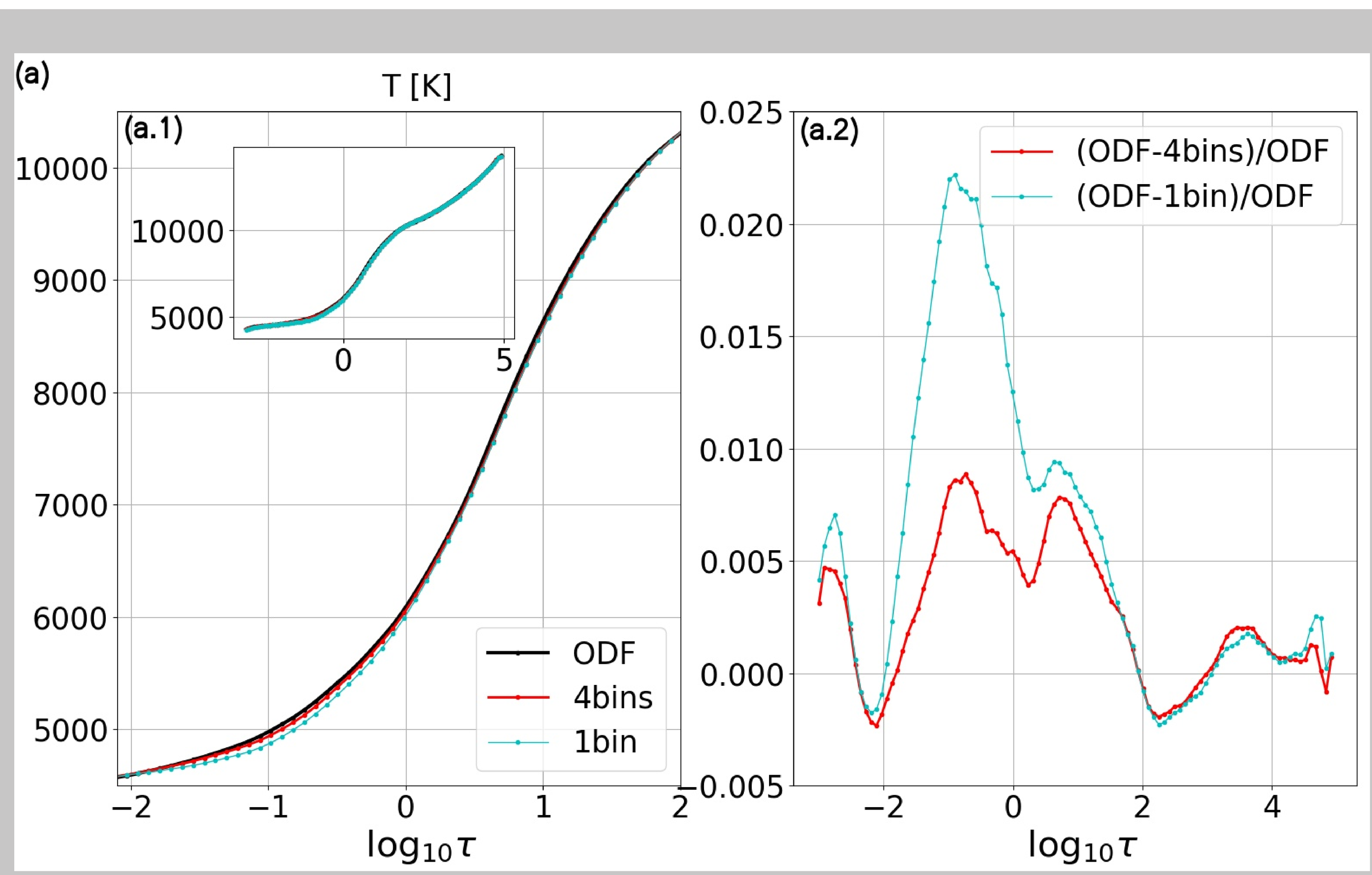


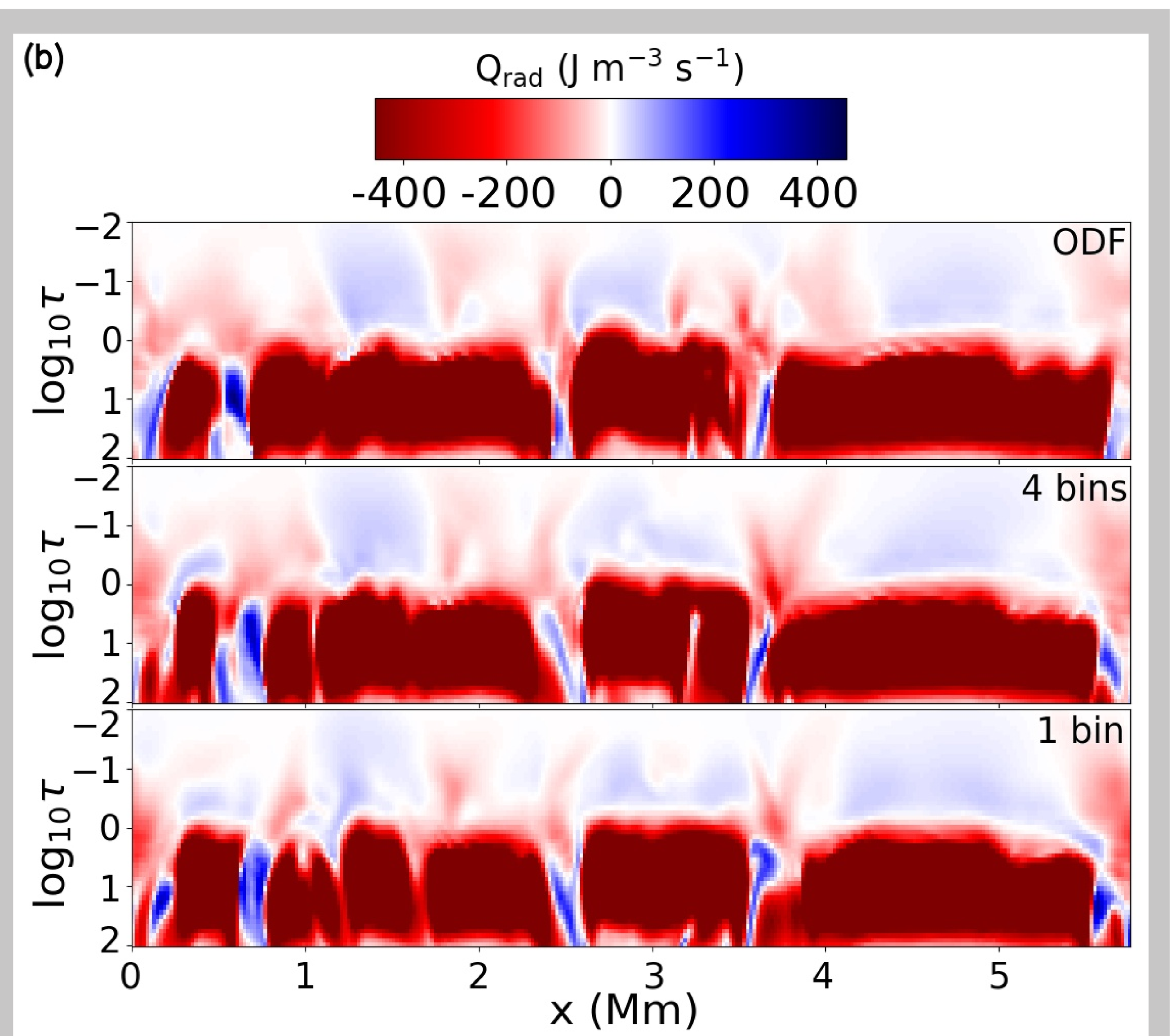
From left to right: **Opacity** in cm^2 g^{-1} for the G-band at 4303-4306 Å, the iron lines around 6300 Å, NaI doublet around 5890 Å and Si and He I lines around 1083 Å. In black line, we show the opacity for a temperature and density of 6400 k and 3.0·10^{-7} g cm^{-3}; in red line, for 4300 k and 7.0·10^{-9} g cm^{-3}. Air wavelengths are shown in the plot.

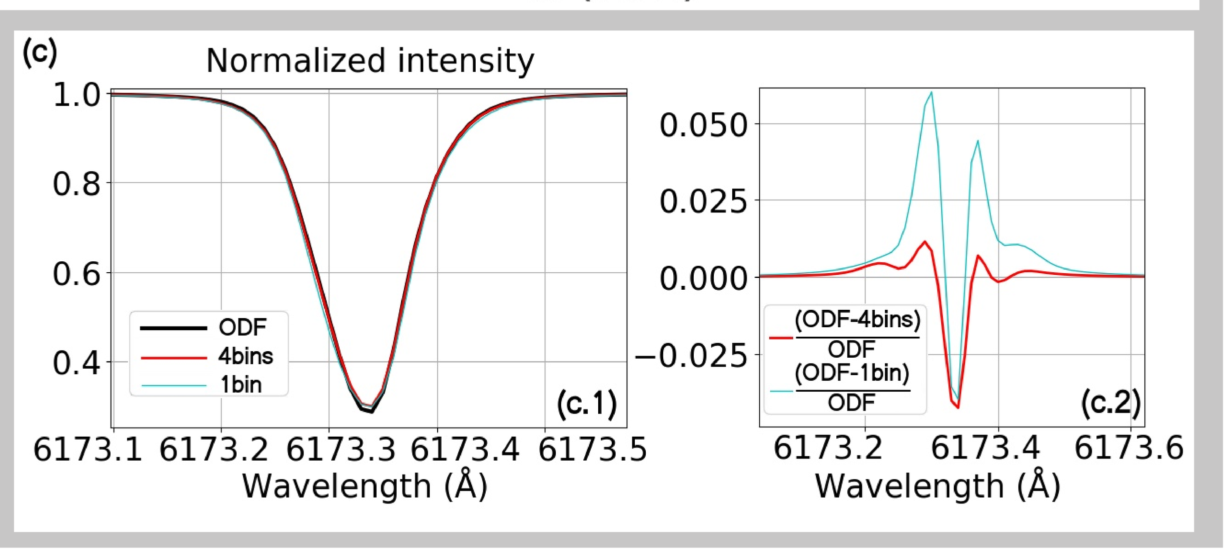




Construction of ODF. First, we divide the wavelength range of the opacity (black line) into steps (grey dashed vertical lines). Then, within each step, we sort every point in terms of opacity (yellow line). Finally, the result is discretized performing the average value in a number of sub-steps (red line). We also transform the wavelength axis into statistical weights within each step, calculated as the width of each sub-step divided by the width of the step (this is needed later in the opacity binning routine).
In the left panel, construction of the ODF for the range 100-20000 Å and temperature, density of 4600 k and 2.9·10^{-8} g cm^{-3}.
In the right panel, zoom-in into the range 4100-4700 Å for the same temperature and pressure.
Notice that the vertical scale is logarithmic.







The pipeline: First, we compute the EOS. For that, we mainly need different atomic and molecular data, the abundances and the temperature (T) and density (ρ) grid. Then, we use Synspec to produce the opacity table in the same T,ρ grid, accounting for the different continuum contributors and including atomic and molecular line lists. We use the resulting opacity table to compute the ODF for different steps in wavelength. Then, we use these ODFs to perform opacity binning, provided a number of bins, using the τ-sorting method and a 1D model of atmosphere. With all these ingredients, we are ready to use MANCHA to run MHD simulations of the near-surface convection of stellar atmospheres, including a realistic radiative transfer treatment.

Results for a solar simulation with the MANCHA code. The same initial snapshot with developed convection (after 2 hours of solar time) was taken to compute the radiative transfer with three different opacity sets for the last 10 minutes: whole ODF table, opacity binned in 4 bins and opacity binned in 1 bin. Thus, we not only appreciate the effect of the opacity table in one iteration, but also with the evolution.
(a.1) Average temperature stratification.
(a.2) Relative temperature differences compared to the whole ODF case.
(b) Radiative heating shown in vertical cuts in the 3D domain of each of the snapshots. Notice how the different opacity tables affect the definition of the structures over the τ=1 surface.
(c.1) Specific monochromatic intensity normalized to the continuum of the **Fe I line** at 6173 Å.
(c.2) Relative difference for the intensity normalized to the continuum of the Fe I line with respect to the result produced using the whole ODF.

Conclusions

We have developed a pipeline that uses Synspec, compatible with our EOS, and produces binned opacity tables, which are necessary to compute simulations of cool stars with MANCHA. We have tested our pipeline for the solar case, checking on the results from the EOS, the opacity table, the ODF and the binning. We are currently working on tests against other ODFs tables, such as ATLAS's. Once we have thoroughly done these latter tests, we plan to check and use the pipeline for main sequence stars with spectral types between F and M. Although the opacity of the stars close to the solar spectral type (G2V) are probably well described with the solar opacity, we expect the opacity of cooler stars to be different from the solar one, specially due to molecular contributions.

References
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