

The STAGGER-grid: A Grid of 3D Stellar Atmosphere Models

I. Methods and General Properties

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ABSTRACT

Aims. We present the *Stagger-grid*, a comprehensive grid of time-dependent, three-dimensional (3D), hydrodynamic model atmospheres for late-type stars with realistic treatment of radiative transfer, covering a wide range in stellar parameters. This grid of 3D models is intended for various applications besides studies of stellar convection and atmospheres *per se*, including stellar parameter determination, stellar spectroscopy and abundance analysis, asteroseismology, calibration of stellar evolution models, interferometry, and extrasolar planet search. In this introductory paper, we describe the methods we applied for the computation of the grid and discuss the general properties of the 3D models as well as of their temporal and spatial averages (here denoted 3D models).

Methods. All our models were generated with the *Stagger-code*, using realistic input physics for the equation of state (EOS) and for continuous and line opacities. Our ~ 220 grid models range in effective temperature, T_{eff} , from 4000 to 7000 K in steps of 500 K, in surface gravity, $\log g$, from 1.5 to 5.0 in steps of 0.5 dex, and metallicity, $[\text{Fe}/\text{H}]$, from -4.0 to +0.5 in steps of 0.5 and 1.0 dex.

Results. We find a tight scaling relation between the vertical velocity and the surface entropy jump, which itself correlates with the constant entropy value of the adiabatic convection zone. The range in intensity contrast is enhanced at lower metallicity. The granule size correlates closely with the pressure scale height sampled at the depth of maximum velocity. We compare the 3D models with currently widely applied one-dimensional (1D) atmosphere models, as well as with theoretical 1D hydrostatic models generated with the same EOS and opacity tables as the 3D models, in order to isolate the effects of using self-consistent and hydrodynamic modeling of convection, rather than the classical mixing length theory (MLT) approach. For the first time, we are able to quantify systematically over a broad range of stellar parameters the uncertainties of 1D models arising from the simplified treatment of physics, in particular convective energy transport. In agreement with previous findings, we find that the differences can be rather significant, especially for metal-poor stars.

Key words. convection – hydrodynamics – radiative transfer – stars: abundances – stars: atmospheres – stars: fundamental parameters – stars: general – stars: late-type – stars: solar-type

1. Introduction

The primary source of information for stellar objects is the light they emit, which carries information about the physical conditions at its origin. However, in order to interpret the information correctly, one first needs either theoretical or semi-empirical models of the atmospheric layers at the surface of stars from where the stellar radiation escapes. Therefore, models of stellar atmospheres are essential for much of contemporary astronomy.

In the case of late-type stars, the theoretical modeling of stellar atmospheres is complicated by the presence of convective motions and turbulent flows as well as of magnetic fields in their envelopes (see review by Nordlund et al. 2009, and references therein). In particular, convection can significantly affect both the atmospheric stratification and emergent spectral energy distribution in these stars. Hence, in order to correctly represent the temperature stratifications in the outer layers of stars, from where the stellar light escapes, it is vital to accurately account

for the interaction between radiative and convective energy transport at the optical surface.

The first realistic grids of line-blanketed atmosphere models for late-type stars appeared with the publication of MARCS (Gustafsson et al. 1975, 2008) and ATLAS models (Kurucz 1979; Castelli & Kurucz 2004). Subsequently, other one-dimensional (1D) atmosphere codes, e.g. PHOENIX (Hauschildt et al. 1999) and MAEAGS (Grupp 2004), were developed to model the atmospheres of stars. In general, these theoretical 1D atmosphere models assume hydrostatic equilibrium, flux constancy, and local thermodynamic equilibrium (LTE). For the modeling of convective energy transport, they commonly employ the mixing-length theory (MLT, see Böhm-Vitense 1958), which is characterized by several free parameters, the most commonly known being the mixing-length l_m , or equivalently, the parameter $\alpha_{\text{MLT}} = l_m/H_p$. Alternatively, some relatives thereof are available, such as the full turbulence spectrum (FTS) theory by Canuto & Mazzitelli (1991), which

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