

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

I. Methods and General Properties

Z. Magic^{1,2}, R. Collet^{2,3,4}, M. Asplund^{2,1}, R. Trampedach⁴, W. Hayek^{1,2}, A. Chiavassa⁵, R. F. Stein⁶ and Å. Nordlund³

¹ Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85741 Garching, Germany
e-mail: magic@mpa-garching.mpg.de

² Research School of Astronomy & Astrophysics, Cotter Road, Weston ACT 2611, Australia

³ StarPlan, Natural History Museum of Denmark/Niels Bohr Institute, Øster Voldgade 5-7, DK-1350 Copenhagen, Denmark

⁴ JILA, University of Colorado and National Institute of Standards and Technology, 440 UCB, Boulder, CO 80309, USA

⁵ Laboratoire Lagrange, UMR 7293, CNRS, Observatoire de la Côte d'Azur, Université de Nice Sophia-Antipolis, Nice, France

⁶ Department of Physics & Astronomy, Michigan State University, East Lansing, MI 48824, USA

Received: ...; Accepted: ...

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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Theory of Stellar Atmospheres Ivan Hubeny, Dimitri Mihalas, 2014-10-26 The most authoritative synthesis of the quantitative spectroscopic analysis of stellar atmospheres This book provides an in depth and self contained treatment of the latest advances achieved in quantitative spectroscopic analyses of the observable outer layers of stars and similar objects Written by two leading researchers in the field it presents a comprehensive account of both the physical foundations and numerical methods of such analyses The book is ideal for astronomers who want to acquire deeper insight into the physical foundations of the theory of stellar atmospheres or who want to learn about modern computational techniques for treating radiative transfer in non equilibrium situations It can also serve as a rigorous yet accessible introduction to the discipline for graduate students Provides a comprehensive up to date account of the field Covers computational methods as well as the underlying physics Serves as an ideal reference book for researchers and a rigorous yet accessible textbook for graduate students An online illustration package is available to professors at press.princeton.edu Nuclear Science Abstracts ,1974

Literature 1981, Part 2 S. Böhme, W. Fricke, I. Heinrich, W. Hofmann, D. Krahn, V. R. Matas, D. Rosa, L. D. Schmadel, G. Zech, 2013-04-18 **Stellar Atmospheres: Theory and Observations** Jean P. de Greve, Ronny Blomme, Herman Hensberge, 1997-10-15 The 1996 Summer School of the European Astrophysical Doctoral Network dealt with the atmospheres of stars the various theories that describe their structure and the interactions with the interior of the stars as well as with the interstellar environment and the observations that support modify and sometimes contradict these theories This volume aims to provide the reader with an insight into problems related to stellar atmospheres both for cool and for hot stars Furthermore it offers opportunities to deal with modern technologies in analysing observational data versus theoretical modelling **Exoplanet Detection Methods** Maximilian Cross, AI, 2025-03-04 Exoplanet Detection Methods offers a comprehensive exploration of techniques used to discover and study planets outside our solar system The book emphasizes optical and spectroscopic methods revealing how these tools bridge theoretical astrophysics with practical applications Two pivotal methods discussed are transit photometry which measures the dimming of a star's light as a planet passes in front of it and radial velocity measurements detecting the subtle wobble of a star caused by a planet's gravity These methods are crucial as combining them reveals a more complete picture of an exoplanet's characteristics The book progresses methodically beginning with fundamental principles like stellar properties and planetary formation then delving into specific detection techniques It covers transit photometry highlighting missions like Kepler and TESS radial velocity measurements and direct imaging including spectroscopic analysis of exoplanet atmospheres A unique aspect of the book is its integration of theory with practical data analysis making it valuable for students and researchers alike The book emphasizes that a complete understanding of exoplanet detection methods is essential to advance the study of planetary formation habitability and the possibility of life beyond Earth **Literature 1980, Part 2** Siegfried Böhme, Professor Dr. Walter Fricke, Inge

Heinrich, Wilfried Hofmann, Dietlinde Krahn, Dorothea Rosa, Dr. Lutz D. Schmädel, Gert Zech, 2013-04-18 **The Interplay Between Massive Star Formation, the ISM and Galaxy Evolution** D. Kunth, 1996 **Recent Advances And Cross-century Outlooks In Physics: Interplay Between Theory And Experiment** Cheuk-yin Wong, Pisin Chen, 2000-04-05 *Catalog* University of Colorado Boulder, 2005 **Transactions of the International Astronomical Union** International Astronomical Union, 1985 **U.S. Government Research & Development Reports**, 1967 *Effects of Mass Loss on Stellar Evolution* C. Chiosi, R. Stalio, 2012-12-06 The IAU Colloquium No 59 The effects of mass loss on Stellar Evolution was held on September 15 19 1980 at the International Centre for Theoretical Physics Miramare Trieste Italy under the auspices of the IAU Executive Committee and the Italian National Council of Research The planning of this conference began two years ago during the IAU Symposium No 83 Mass loss and evolution of O type stars Qualicum Beach Victoria Canada when we felt that mass loss and its effects on the evolution of stars was too broad a subject for being confined to O type stars only Therefore we thought that a conference dealing with the general problem of mass loss across the whole HR diagram would have been of interest to all people working in the field The main idea was that bringing together Astronomers and Astrophysicists of the widest range of interests and expertise all in some way related to the problem of mass loss from stars would have spurred thorough discussions on the many aspects and implications of this topic We hope this goal has been achieved Furthermore the most recent observational and theoretical developments on the problem of mass loss from early type stars avoided this meeting to be a simple updating of the Qualicum Beach Symposium as far as this issue is concerned **Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical Or Physical Character**, 1929 *Smithsonian Contributions to Astrophysics*, 1956 *Beyond Earth's Borders* Barrett Williams, ChatGPT, 2025-03-07 Embark on an interstellar journey with *Beyond Earth's Borders* a compelling exploration of one of humanity's most profound quests the search for life beyond our home planet This ebook navigates the intriguing landscape of astrobiology presenting the latest discoveries and theories that are redefining our understanding of the universe Begin with the opening chapters that illuminate the foundational questions driving astrobiology Delve into humanity's age old quest to discover what truly constitutes life and uncover the cosmic conditions necessary for it to thrive As you turn the pages you'll find yourself transported to Mars Earth's enigmatic neighbor to examine the tantalizing evidence hidden in Martian meteorites Explore the resilient world of extremophiles on Earth and ponder what these organisms reveal about life's potential on other worlds Venture further into the cosmos to discover exoplanets and their varying habitability indices offering a kaleidoscope of possibilities for life beyond Earth The ebook also takes you through the role of cutting edge technology in astrobiology from the advancements in space exploration to the powerful telescopes scanning distant worlds Journey beneath the icy crusts of Europa and Enceladus where subsurface oceans may harbor secrets yet to be uncovered Engage with the profound ethical and philosophical questions that arise when

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Physical Processes in Red Giants I. Iben, Alvio Renzini, 2012-12-06 In recent years it has become clear that the red giant phase is one of the most dramatic periods in a star's life when all of its parts become involved in ways that have both direct and indirect observational consequences This is most particularly true of low and intermediate mass stars during the second ascent of the giant branch Such stars bring to their surfaces products of nucleosynthesis currently taking place in their deep interiors they pulsate as Mira variables develop extended outward flowing atmospheres that may exhibit maser properties and shed great quantities of matter sometimes highly processed into the inter stellar medium The manner in which processed matter is brought to the surface is far from being completely explained and the precise mechanism or mechanisms whereby matter is ejected from the stellar surface whether by deposition of Alfvén waves radiation pressure on grains or as a consequence of some large scale envelope instability has yet to be elucidated to everyone's satisfaction The purpose of the second workshop in Astrophysics organized by the Advanced School of Astronomy was to bring together experts on all the physical processes occurring in red giants in an effort to emphasize the interrelatedness of these individual processes and to encourage a dialogue among experts that might serve to initiate a synthesis or at least sharpen our understanding of the most important problems to address in the future

Reports on Astronomy 2006-2009 (IAU XXVIIA) Karel A. van der Hucht, 2009-03-23 The Transactions XXVIIA Reports on Astronomy 2006-2009 provides a comprehensive and authoritative review of what has been achieved in astronomy during the years 2006 to 2009 These insightful and up to date reviews have been written by the presidents and chairpersons of the IAU scientific bodies the Divisions the Commissions and the Working Groups Topics covered in this wide ranging volume include fundamental astronomy the Sun and heliosphere planetary sciences stars variable stars interstellar matter the Galactic system galaxies and the Universe optical and infrared techniques radio astronomy space and high energy astrophysics and other IAU activities The reviews have been written at a level suitable for colleagues in the same fields but will also be useful for students and researchers wishing to gain an overview of astronomical fields beyond their own research area

Mechanisms of Chromospheric and Coronal Heating Peter Ulmschneider, Eric R. Priest, Robert Rosner, 2013-06-29 One of the great problems of astrophysics is the unanswered question about the origin and mechanism of chromospheric and coronal heating Just how these outer stellar envelopes are heated is of fundamental importance since all stars have hot

chromospheric and coronal shells where the temperature rises to millions of degrees comparable to the temperatures in the stars cores Here for the first time is a comprehensive inventory of the proposed chromospheric and coronal heating theories The proposed heating processes are critically compared and the observational evidence for the various mechanisms is reviewed This is essential reading for all those working in such fields as stellar activity radio and XUV emission rotation and mass loss for whom a detailed and consistent presentation of our knowledge of chromospheric and coronal heating mechanisms is urgently needed

Asymptotic Giant Branch Stars Harm J. Habing, Hans Olofsson, 2013-04-17 This book deals with stars during a short episode before they undergo a major and fatal transition Soon the star will stop releasing nuclear energy it will become a planetary nebula for a brief but poetic moment and then it will turn into a white dwarf and slowly fade out of sight Just before this dramatic change begins the star has reached the highest luminosity and the largest diameter in its existence and while it is a star detectable in galaxies beyond the Local Group its structure contains already the inconspicuous white dwarf it will become It is called an asymptotic giant branch star or AGB star Over the last 30 odd years AGB stars have become a topic of their own although individual members of this class had already been studied for centuries without realizing what they were In the early evolution so called E AGB phase the stars are a bit bluer than but otherwise very similar to what are now called red giant branch stars RGB stars It is only in the second half of their anyhow brief existence that AGB stars differ fundamentally from RGB stars

Worlds Beyond Barrett Williams, ChatGPT, 2025-05-23 Title Worlds Beyond Discover the enigmatic realms of exoplanets in Worlds Beyond an immersive journey into the universe's untold stories This captivating eBook is your ticket to exploring the cosmic wonders that orbit far beyond our solar system unlocking the mysteries of distant worlds and the potential for life beyond Earth Begin your adventure as you delve into the intriguing history and science of exoplanet discovery unraveling the methods used to detect these distant orbs Whether it's through the precision of the transit method or the analytical prowess of radial velocity techniques you'll gain a profound understanding of the tools astronomers use to uncover hidden planets Venture into the Goldilocks Zone where conditions might just be right for life Uncover the secrets of habitable worlds and the role liquid water plays in fostering life all while exploring the stars and zones that make these conditions possible Dive deeper into the cosmos with an exploration of spectral signatures and atmospheric analysis Learn how scientists read the language of light to detect atmospheric compositions and potential biomarkers sparking the age old question Are we alone Marvel at the astonishing diversity of exoplanetary systems from hot Jupiters to rogue planets each painting a vivid picture of our universe's vastness Discover the roles that powerful space telescopes and ground based observatories play in revealing the grandeur of worlds beyond our own Worlds Beyond also invites you to ponder the profound implications of discovering extraterrestrial life and alien technology Engage with the philosophical and ethical considerations that arise as humanity seeks cosmic contact This eBook bridges the gap between science and imagination highlighting exoplanets in culture science fiction and

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