Stellar Hydro Days IV: Abstracts

Isabelle Baraffe: Multi-dimensional fully compressible, time implicit simulations of hydrodynamical processes in stars

I will present the recent development of a multi-dimensional, fully compressible hydrodynamical time implicit code, the MUSIC code, devoted to stellar and planetary interiors. I will discuss the main challenges in the computations of multi-dimensional stellar structures and some of the advantages of our approach with MUSIC for the study of stellar fluid dynamics problems. MUSIC is interfaced with our stellar evolution code and with MESA, which provide initial 1D stellar structures for any type of star and allow exploration of a wide range of stellar phases and masses. I will present our first applications to a variaty of problems, namely accretion process on young low mass stars, 2D/3D compressible envelope convection and overshooting in pre-MS stars, stellar rotation and its effect on convection and shear instabilities. A major motivation for these studies is to derive new prescriptions to be implemented in stellar evolution codes and to be tested against various observational constraints. I will show the success of this approach with MUSIC for the accretion problem and for the treatment of overshooting in pre-main sequence stars within the context of lithium depletion in the Sun and in solar-like stars.

Simon Campbell: First attempts at 3D simulations of core helium burning stars

Our best 1D models of core helium burning stars are quite uncertain, and, up until recently, poorly constrained by observations. These uncertainties propagate to the later phases of stellar evolution, undermining the accuracy of models of supernova explosions and red giants. Also, since they are relatively numerous and luminous, core helium burning stars feature disproportionately in stellar surveys and in integrated light from galaxies. Thus good models of this phase are needed. Here I review the uncertainties in the 1D models and present our first attempts at a 3D hydrodynamics simulation of a core helium burning star, from which we hope to gain insight as to how to improve the 1D modelling.

Andrea Cristini: ILES of shell carbon burning

In order to study in detail the structure of convective boundary regions and the mixing that occurs across them, we present three-dimensional hydrodynamic simulations of the carbon burning shell within a 15 solar mass star. We simulate the shell on progressively finer grid meshes, up to a maximum of 1,024 grid points in each direction. We show that convective boundary mixing (CBM) occurs through turbulent entrainment and interpret our results within the framework of the entrainment law. We conclude that a radial resolution of 512 zones is adequate to resolve the upper boundary, but 1,536 zones would be required to resolve the lower boundary. We estimate the widths of the upper and lower boundaries to be 29% and 11% of the local pressure scale heights, respectively. We argue that the results of this and similar studies point to the need for new CBM prescriptions in stellar evolution models.

Joshua Dolence: Results of core-collapse modeling for a variety of progenitors

I will present results obtained with the state-of-the-art neutrino radiation hydrodynamics code Fornax for the outcome of collapse for a large number of progenitors. Systematic trends with progenitor properties will be explored, including recently proposed metrics like core compactness.

Philipp Edelmann: Hydrodynamics of Dynamical Shear Instabilities in Massive Stars

Co-authors: F. K. Roepke, R. Hirschi, C. Georgy, S. Jones

Through redistribution of angular momentum and chemical composition, rotationally induced instabilities have an important impact on the evolution of many stars, particularly massive ones. It is thus important to include their effect in stellar models. As most work in stellar evolution is done in 1D, the common approach is to include instabilities as additional diffusion coefficients. The value of these coefficients cannot be easily determined using theoretical considerations, but hydrodynamical simulations can provide valuable insights here.

I will present our recent 2D simulations of the development of a dynamical shear instability in the high Péclet number regime (arXiv 1704.06261). For the initial condition we used a 20 solar mass model after core oxygen burning computed with the Geneva stellar evolution code (GENEC). The hydrodynamics of the instability were followed using the Seven-League Hydro (SLH) code. We observe the instability start in the same region as predicted by linear theory and compare its development with the predictions of the prescription used in GENEC. We also extract an effective diffusion coefficient from the change in the angular averages of the composition. We find generally good agreement with the diffusion approximation but the results suggest that the criterion for applying this diffusion should be refined to include neighbouring regions. In addition to these results, I will discuss issues in mapping 1D shellular rotation models to 2D and 3D grids used in hydrodynamics codes.

Christopher Fryer: Stellar Convection and the Supernova Explosions

Understanding convection in stars plays an important role in the supernova engine from determining the entropy of the collapsing core to providing seeds for later turbulence seen in the supernova explosion. I will review current studies of how features of stellar convection affect supernova explosions and the analysis of supernova observations.

Cyril Georgy: Convection in massive stars

In this talk, I present our ongoing effort in order to simulate deep convective regions during the advanced stages of massive star life at high resolution. I will provide a broad overview of the current status of the treatment of convection in classical 1d codes, and show how the adopted treatment (penetrative overshoot, convective overshoot, Schwarzschild or Ledoux criterion, ...) affects the results of the computation, leading to very different evolutionary paths and blurring our capacity to predict the evolution of massive star satisfactory. This illustrates the need for a better understanding of convection inside massive star, that can be obtained with the guidance of multi-d hydrodynamics simulations.

In this context, our recent results for convective carbon-burning shell (Cristini et al.) and neon-burning have shown the limitation of the classical mixing-length theory approach. I will show preliminary results of convective neon-burning shell we are currently computing with the PROMPI code, following the approach of our carbon-burning simulations. I will then discuss briefly the status of our efforts in trying to develop new prescriptions for convection in massive stars, to be implemented in 1d codes, better capturing the average behaviour of our multi-d simulations.

I will also discuss some observational tests that could be useful to validate new prescriptions for convection. In particular, the behaviour of the intermediate convective hydrogen-burning shell leads to very different properties in terms of chemical composition of the surface of blue and red supergiants.

Falk Herwig: Hydrodynamic nuclesoynthesis and observational constraints for CBM

Through hydrodynamic simulations a new picture emerges how nucleosynthesis and convection can interact, and new modes of nucleosynthesis can be possible. In the late phases of the evolution low-mass and massive stars convective-reactive nucleosynthesis provides pathways to produce abundance patterns associated with i-process conditions, as well as odd-Z element production in the O-C shell mergers in massive stars. Another aspect of convection that has observable consequences is convective boundary mixing (CBM), and I will discuss several examples that demonstrate how CBM effects the nucleosynthesis and other observable outcomes of stars.

Johann Higl: Simulating Hydrogen Burning Cores in Low Mass Stars

One of the biggest uncertainties in determining ages of stellar models is the duration of the hydrogen burning phase, which can vary up to 20% depending on the overshooting parameter used. In order to get more accurate data, we need to simulate stars in this burning phase and update the currently used parametrized descriptions with a 321D link. Mixing length theory predicts that velocities in these cores are very sub sonic, which makes MAESTRO the theoretically ideal tool to simulate several convective turnover times. As it turns out this is not as straight forward as initially thought, because such a low mach number code does not properly resolve internal gravity waves. While this is usually not a big problem in simulations of more massive stars, the stellar stratification in low mass stars has a maximum in the Brunt-Väisälä frequency relatively close to the convective boundary. In this talk I will show that such a cavity for gravity waves allows for a non-linear growth of gravity waves if a low mach number scheme is used and how to suppress this effect with an appropriate time stepping.

Delphine Hypolite: The 2D dynamics of the radiative envelope of massive stars

Co-authors: Stephane Mathis, Michel Rieutord

Asteroseismology has opened new windows on stellar interiors by probing the internal differential rotation of massive stars. However, detecting and characterizing the differential rotation deep within the star remains quite a challenging task. Moreover, the precise nature of the interactions and couplings between the convective core and the radiative envelope is still poorly understood.

To build upon our current understanding of these interactions, we have constructed new 2D models of their radiative envelope in which we study the influence of a differentially rotating convective core upon its overall dynamics. We take into account the shear at the convective-radiative interface computed by 3D simulations of convective core of massive stars. We provide a 2D coherent description of the dynamics in the radiative zone with an ab-initio computation of the differential rotation and meridional circulation that are induced because of the shear imposed by the convective core at the bottom of the radiative envelope.

Studying first an incompressible fluid, we describe the spin-up flow arising from this shear. Stewartson layers, which arise upon the tangent to the core cylinder like in a spherical Couette apparatus, play a key role in the transport of angular momentum. The differential rotation is highly influenced by the shear of the convective core mainly inside the tangent to the core cylinder and the rest of the envelope rotates quasi uniformly. We present how to characterize the corresponding asteroseismic signatures and provide a prescription for the flux of angular momentum due to the spin-up flow suitable for 1D stellar models. When using the Boussinesq approximation, we provide the range of parameters where the spin-up flow induced by the convectively driven shear at the convective-radiative interface may overcome the baroclinic flow arising from the stable stratification within the main-sequence lifetime. We describe the shear instabilities that may destabilize the flows and discuss how to improve the current modelling of the radiative envelope of massive stars. This is an essential task to draw a coherent picture of stellar evolution in the whole HR diagram.

Samuel Jones: Modelling stars near the electron-capture supernova limit

The progenitor stars of supernovae are in many aspects still poorly understood. In particular, the fate of stars near the electron-capture supernova limit between white dwarf and neutron star formation is one of the poorest understood. Stellar evolution codes are an invaluable tool with which to study the long term evolution of supernova progenitors, however they necessarily rely on the assumption of spherical symmetry and approximations for temporally and spatially unresolvable processes.

I will review the current status of modelling the evolution of stars close to the electron-capture supernova limit, including the limitations of current models and some of the recent developments in trying to address them. These include improved nuclear physics input and targeted hydrodynamic simulations of both the oxygen deflagration phase and convective boundary mixing.

Catherine Lovekin: Constraining stellar convection using asteroseismology

Coauthors: J.A. Guzik, J. Tompkins

The effects of rotation on pulsation in delta Scuti and gamma Doradus stars are poorly understood. Stars in this mass range span the transition from convective envelopes to convective cores, and realistic models of convection are thus a key part of understanding these stars. We use Period04 to calculate the frequencies based on short and long cadence Kepler observations of gamma Doradus and delta Scuti stars. We use the modular stellar evolution code MESA to produce stellar models between 1.2 and 3.5 solar masses with varying amounts of rotation and convective overshoot. Pulsation frequencies are calculated using GYRE. Comparison of these models with the observed pulsation frequencies of the stars allows us to place constraints on the age, mass, convective core overshoot, and rotation rate of these stars. These 1D fits can be further refined with two-dimensional models using ROTORC and NRO.

Bernhard Mueller: The Role of Multi-D Stellar Evolution for the Core-Collapse Supernova Explosion Mechanism

In this talk, I will review the potential role of large-scale seed perturbations in active convective burning shells in the core-collapse supernova explosion mechanism. Based on recent 3D simulations of O shell burning and supernova simulations with multi-group neutrino transport, 3D initial conditions may play a decisive beneficial role for fostering neurino-driven explosions in some, but not in all progenitors. This is supported by a survey of 1D stellar evolution models. I will also dicuss the influence of resolution in models of the last minutes of oxygen shell burning. Changes in the pre-supernova core structure due to convective boundary mixing remain a major uncertainty, though. Based on analytic estimates, I argue that the readjustment of the shell structure during carbon burning may be of particular interest.

May Pedersen: Constraining the shape of convective core overshooting using slowly pulsating B-type stars

During ~90% of their evolution, massive stars are highly influenced by internal mixing processes occurring in and near their convective cores, such as convective core overshooting. Unfortunately, our understanding of these processes is poor and the number of useful test cases limited, therefore providing the largest uncertainties in stellar structure and evolution models for massive stars. Asteroseismology, the probing of stellar interiors using the pulsations of the stars, offers the tools we need to constrain such internal mixing processes. Gravity modes (g-modes) in particular have considerable amplitudes throughout the entire interior of the star and are highly sensitive to the amount of mass in the overshoot layer, as well as to the chemical gradient left behind as the convective core retreats during the main-sequence evolution. The value of and deviations from uniform period spacings of such modes provide information on the mixed core and additional mixing processes just above it.

With this talk we aim to show and explain how the choice of the description of the convective core overshooting influences the shape of the theoretically predicted period spacing series. Furthermore we will investigate any correlations which may exist between the descriptions. For this study we will focus on three overshooting descriptions (step, exponential and extended exponential overshooting), which are currently implemented in the state of the art stellar structure and evolution code MESA.

Vincent Prat: Shear-driven turbulent transport in stellar radiative zones

Stellar models play an important role in many fields of astrophysics, from the chemical evolution of galaxies to the characterisation of planetary systems. However, these models present large uncertainties due to our lack of understanding of stellar evolution. In particular, magneto-hydrodynamical processes that transport chemical elements and angular momentum in stellar interiors are often poorly (or not at all) modelled in stellar evolution codes. In this context, numerical simulation is a crucial tool to provide additional constraints on such models and thus to improve the predictive power of stellar evolution theory.

Turbulence generated by the shear instability in stellar radiative zones is one of the processes that have been thought to induce transport in stellar interiors. This transport, often called rotational mixing, was first modelled by Zahn (1992, A&A, 265, 115) using phenomenological arguments. Recent asteroseismic observations show that such models may underestimate the transport by several orders of magnitude. The work that I will present consists in performing numerical simulations of the shear instability to test existing models and in proposing new prescriptions. In particular I will review the results obtained about the effects of the key physical ingredients that are thermal diffusion, stable stratification (thermal and chemical), and viscosity on vertical transport. I will also present a new theoretical model of horizontal transport that includes for the first time rotation, stable stratification and shear, and discuss the impact of this new prescription on stellar evolution.

Fritz Roepke: Low Mach number fluid dynamics for stellar applications with the Seven-League Hydro code

Flows in stellar interiors are often characterized by low Mach numbers. This causes problems in simulating them with conventional approaches to computational fluid dynamics. A scheme that can be applied to problems arising from stellar evolution theory has to be able to follow such flows on time scales that are very long compared to the sound crossing time. This issue can be addressed with implicit time discretization. Another problem is caused by the excessive dissipation conventional Roe-type hydrodynamics solvers exhibit at low Mach numbers. I will show that this arises from a wrong scaling of the involved numerical fluxes with Mach number and point out a way to cure this problem. The resulting method is still based on the full equations of compressible fluid dynamics and can therefore be seen as an all-Mach number solver.

These numerical schemes have been implemented into the Seven-League Hydro (SLH) code, which, together with other features, makes it a suitable tool to study processes in stellar evolution with multi-dimensional simulations. A few illustrative examples of applications will be given.

Timothy Van Reeth: The interior rotation of intermediate-mass stars

Gamma Doradus stars are intermediate-mass stars with a convective core and a convective core that exhibit gravity-mode pulsations, which are sensitive to the properties of the near-core regions in the deep stellar interior. By analysing these pulsations, we can study the interior structure of these stars, and test stellar structure and evolution theory in this mass range, in particular concerning the rotational mixing and angular momentum transport mechanisms. Over the last decade, photometric observations with space missions such as CoRoT and Kepler have provided us with unprecedented opportunities in this field.

Using the traditional approximation to treat the influence of stellar rotation on pulsations, we have developed methodology to derive the near-core rotation rate from observed gravity-mode pulsation periods and identify the pulsation mode geometry. This is an absolute requirement for detailed theoretical modelling of these stars. We succesfully applied our technique to 40 targets in a sample of 50 gamma Doradus stars, allowing us to do ensemble modelling. The majority of the observed pulsations were found to be prograde dipole modes, which travel in the direction of the rotation, and the derived rotation rates cover a large range of possible values. In ten of the studied stars, our analysis resulted in the detection and identification of Rossby modes, purely inertial pulsations which travel in the direction opposite from rotation. This is the first time these modes have been found in gamma Doradus stars.

This analysis forms the first step towards detailed seismic modelling of observed pulsation period spacing patterns in individual gamma Dor stars.

Paul Woodward: Simulation of Convective Boundary Mixing with PPMstar

My team at Minnesota is working with Falk Herwig and his team at Victoria to simulate the mixing into a turbulent convection flow of stably stratified gas from just outside the convection zone. Our special focus is on circumstances where this mixing can lead to ingestion of new fuel into the convection zone, with subsequent combustion in a convective-reactive regime. In this regime, the time scales for nuclear burning and for the turn-over of large eddies are comparable. This is a regime in which i-process nucleosynthesis can occur, and it is also a regime in which we have found large departures from approximate spherical symmetry. I will discuss two major challenges that these studies pose for computation and describe how we have designed PPMstar to address them. The first is the need to compute with accuracy and with confidence the very small entrainment at the convective boundary of stably stratified gas. To address this challenge, we utilize PPB moment-conserving advection of the mixing fraction variable. This provides an explicitly updated sub-grid-cell structure for this special variable with high formal order of accuracy as well as special properties at thin multifluid interfaces. Our second challenge is that the flows of interest involve Mach numbers in a regime where implicit numerical techniques do not offer clear advantages, but explicit techniques are not at their best either. I will illustrate these challenges through examples where we have simulated hydrogen ingestion flashes in AGB stars. Convergence of the gas entrainment rate, even with our elaborate treatment of the multifluid mixing region, requires large and expensive computations. These flows are characterized by long, gradual approaches, with typical flow Mach numbers of 0.05, leading to outbursts in which Mach numbers increase to 0.1 and ultimately to as high as 3. To handle the long approach to such outbursts, our strategy is to exploit the explicit formulation of our numerical methods to make the PPMstar code run very fast and scale to 14,000 nodes. This has proved successful with our first target problems. Enhancements of the code, now well underway, to handle still more challenging problems will be outlined. These include the ability to run on GPUs and a three-level AMR implementation that we believe can scale efficiently to 20,000 nodes.

Michael Zingale: Modeling Stellar Convection and Explosions with Maestro, Castro, and the BoxLib/AMReX Astrophysics Suite

Stellar explosions come in a wide variety, powered by either by gravitational collapse or thermonuclear energy release. These are truly multiphysics problems---modeling them requires the coordinated input of gravity solvers, reaction networks, transport, and hydrodynamics together with microphysics recipes to describe the physics of matter under extreme conditions. Furthermore, these models involve following a wide range of spatial and temporal scales, which puts tough demands on simulation codes. As a result, a variety of methods have been developed to model the different phases of these explosions. In this talk, I describe the suite of codes built around the BoxLib (and soon AMReX) adaptive mesh refinement framework: Maestro, suited for modeling subsonic flows that precede the explosions, and Castro, which models the (radiation-driven) explosive phases.

I will show examples from both Maestro and Castro, including models of convection in X-ray bursts, the pre-explosion phase of both the Chandra and sub-Chandra model of Type Ia supernova, and ongoing work on merging white dwarfs. I will also discuss the current computational challenges and future algorithmic directions of both codes, including our plan for the exascale and new physics developments.