Improved magnetoconvection models for precision astrophysics

Context & Aims Current and next-generation space- and ground-based observatories are revolutionizing precision observations in astrophysics. Lightcurves from *Kepler* and *TESS* [39] have enabled the detection of thousands of planets [21], and ESA's *PLATO* will gather up to a million stellar lightcurves in search of Earth analogues [32]. Spectroscopic follow-up observations will soon be sensitive enough to detect the radial velocity signal of Earth-like planets around Sun-like stars [~ 10 cm/s, 13]. These datasets have fueled a rapid expansion of the field of asteroseismology, which can probe the radial dependence of mixing processes in stellar interiors [33]. Mixing processes which bring fresh fuel into the stellar core affect subsequent stellar evolution and the mass of the eventual stellar remnant, so mixing uncertainties affect predictions of the populations of white dwarfs, neutron stars, and black holes. Kilometer-scale gravitational wave observatories (e.g., *LIGO*/*VIRGO* and soon *Kamioka*) will continue to challenge models with new constraints on the populations of massive remnants [1]. Proposed space-based gravitational-wave observatories (*LISA*) will complement these observations with extreme sensitivity to the galactic white dwarf population [40].

Discoveries ranging from exoplanets to black holes rely on high-precision stellar evolution models [23], and convection introduces uncertainty into these models. Mixing at the convective core boundary of massive stars ($M_* \gtrsim 1.1 M_\odot$) lead to core mass uncertainties of up to 70% [25], resulting in evolutionary pathway uncertainty. Luminosity variations from surface convective patterns on less massive stars can completely cover the signals of e.g., planets in radial velocity measurements [13]. These processes and signals result from nonlinear 3D magnetoconvection, which is poorly modeled in stellar evolution calculations and theoretical prescriptions. **Modern precision observations have revealed major theoretical shortcomings in models of convection and demand a new state-of-the-art set of convective simulations.**

The goal of this proposal is to build a next-generation set of global and local 3D numerical simulations, which will answer the following three questions:

1. How large are convective cores in massive stars?
2. How does magnetoconvection affect the radii of low-mass, fully convective stars?
3. How does surface convective blueshift vary across stellar mass?

Below I describe how these questions can be answered, why my expertise enables me carry out these investigations, and why the University of Exeter is the ideal host institution for these studies.

Focus I: Convective Boundary Mixing Observations consistently demonstrate a need for improved models of convective boundary mixing (CBM) [24]. Stellar models require an unexplained mass-dependent CBM to reproduce observed eclipsing binary populations [12]. The amount of CBM used in stellar evolution models determines the main sequence width on the HR diagram and thus the stellar lifetime, luminosity, and effective temperature [11, 20]. Asteroseismology directly probes the results of CBM, revealing extensive mixing near convective core boundaries, and that *both* entropy and chemical composition mix in a process called "convective penetration" [31, 33]. Models also require extra mixing in low mass stars with convective envelopes; lithium ignites at a greater depth than the estimated convective boundary, but observed lithium abundances suggest that convective motions reach the lithium ignition depth [34, 7].

To address these modeling deficiencies, I will create simulations of the cores of massive stars using the *Dedalus* [10] code. These simulations will differ from past simulations of massive stars, because they will include the full "ball" geometry of the convective core and they will be relaxed into thermal equilibrium. *Dedalus* was recently updated with the state-of-the-art ability to simulate flows that pass through the coordinate singularity at $r = 0$ in spherical coordinates [42, 28]; most prior codes used a spherical shell geometry with a small interior "cutout" of the core. Regarding thermal equilibration, my previous CBM studies [3, 4] demonstrated that the structure of boundary mixing regions can take thousands of convective overturn times to saturate. Fortunately, I have developed methods of "accelerated evolution" [2]; these techniques allow me to achieve thermally equilibrated solutions while saving up to an order of magnitude in computational resources.

The University of Exeter is a particularly exciting location to undertake this project, because it is complementary to ongoing work in the group of Prof. Baraffe. Prof. Baraffe's group will use the

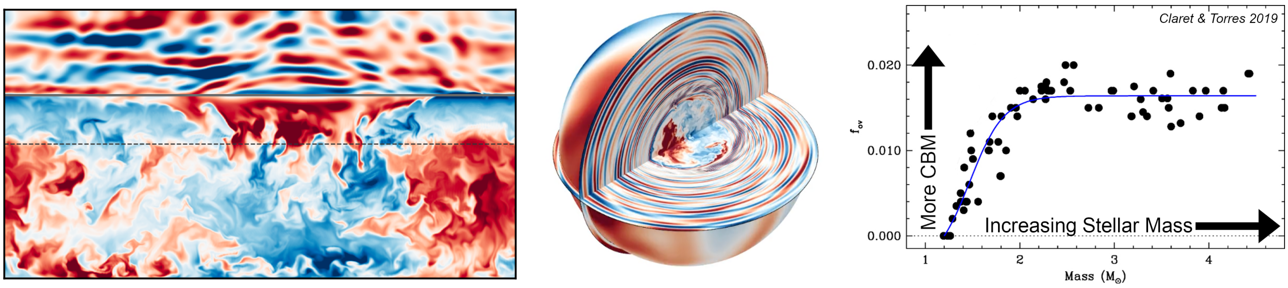

Figure 1: (Left) The temperature in a convective boundary mixing simulation from my previous work in Cartesian geometry [3]. Note the boundary mixing region between the dashed and solid lines where where the hot, red upflows turn cold. (Middle) A visualization of entropy perturbations in a 40 $M_\odot$ star *Dedalus* simulation I created. Note the core convection zone where flows pass through $r = 0$ and the stable gravity wave region outside the core. (Right) Inferred convective boundary mixing from eclipsing binaries; note the strong mass dependence from $M_* = 1.1 - 3M_\odot$ [12].

MUSIC code to survey the effects of rotation and magnetism on convective boundary mixing in 3-20 $M_\odot$ stars in the coming years. This provides an excellent opportunity to compare the results of codes solving nearly identical equation sets but in slightly different geometries (*Dedalus* includes $r = 0$; *MUSIC* has an inner cutout). Combining my expertise with that already present at Exeter will allow us to make progress on this decades-long problem in stellar astrophysics.

Task 1: I will study convective penetration [Fig 1, left, 3], in fully compressible simulations whose background stratifications are based upon MESA models of massive stars (as in Fig. 1, middle). In this first year, I will focus on the purely hydrodynamical (HD) case, and I will focus on stars ranging from $1.1 - 3M_\odot$, where observed "extra mixing" is a strong function of stellar mass [Fig. 1, right, 12].

Task 2: I will incorporate magnetohydrodynamic (MHD) effects into my code and compare HD and MHD results for stars in the $1.1 - 3M_\odot$ range. I am particularly interested in the effects of Ohmic dissipation. In our current theory of CBM via convective penetration [3] the mixing region's size depends on the dissipation in the convection zone. I therefore predict that the MHD simulations should have smaller mixing regions than the HD simulations due to Ohmic dissipation, but magnetism may change the convective flows in interesting ways to compensate for this effect. These experiments will help determine how strong core magnetic fields [29] affect CBM, core mass, and the eventual stellar remnant formation. I will also study select $3 - 20M_\odot$ stars and collaborate with Prof. Baraffe's group to compare my *Dedalus* simulations to *MUSIC* simulations, and create a benchmark for the benefit of outside research groups.

Deliverable: **The first 3D MHD simulations of core convection in massive stars that include the coordinate singularity at $\boldsymbol{r = 0}$.** These models will be used to create a 1D implementation of convective boundary mixing informed by realistic simulations in the proper geometry, significantly improving the limited model we presented in [3]. I will also publish an open-source, fully compressible *Dedalus* module which can solve HD and MHD equations in massive stars, so the community will have straightforward access to a tool to use for studying dynamics in massive stars.

Focus II: Radius Inflation Low mass stars are inflated relative to model predictions [22], which can introduce errors as large as a factor of two into the determination of young stellar cluster ages [16]. Stabilizing magnetic effects [17, 18] can make models better match observations [41], but it is unclear if 1D magnetic prescriptions accurately model 3D magnetohydrodynamics. There are now constraints on the surface magnetic fields of many stars, including hundreds of M dwarfs [37]. M dwarf stars are the vast majority of stars in the galaxy [19] and are a major target in the search for habitable exoplanets [e.g., 36]. Magnetic models of fully convective stars should be revisited taking into account the novel measurements of surface magnetic fields.

Magnetoconvection simulations of fully convective stars have occasionally been performed for many years [9, 43]. These models often included a cutout sphere near $r = 0$ and hard bottom boundary, making them not quite fully convective. Select new simulations [8, 26] include the proper geometry, but only examine the growth of a dynamo field from a weak seed field, so it is difficult to compare their evolved fields to observed stellar fields. Furthermore, most prior global magnetoconvection models have included heat-transporting thermal boundary layers, but boundary-driven convection has consistently failed to reproduce the "ultimate" dissipation-free scaling laws of heat transport expected in astrophysical systems [35]. Convection driven by internal heating and cooling layers can achieve astrophysical dissipation-free scalings [6, 14, 27], but no internally-driven strong-field magnetoconvection studies have been performed. I will build internally-driven simulations in the proper full-ball geometry with strong fields informed by stellar surface observations. Exeter is the ideal place to build these simulations, because I can collaborate with Prof. Browning who is an expert on M-dwarf simulations [9], and who has incorporated magnetic effects into 1D stellar models [22].

Task 3: I will study MHD simulations of fully convective M dwarf stars subject to strong imposed magnetic fields. While some dynamo action will occur in these simulations, they will be initialized with magnetic fields that align with observed stellar magnetic fields strengths [37], providing insight into magnetoconvection under stellar conditions. Convection will be driven by nuclear burning (internal heating) and a model of radiative losses at the surface (internal cooling). I will examine whether magnetism affects the heat transport and thermal stratification of these stars, and test whether 1D magnetoconvection prescriptions [e.g., 17, 18] are commensurate with 3D MHD simulations.

Deliverable: **The first strong-field magnetoconvection models of M dwarf stars spanning the full stellar domain, including $r = 0$.** These models will experimentally test and validate current 1D magnetoconvection models and prescriptions.

Focus III: Convective Blueshift An Earth-like planet around a Sun-like star produces a radial velocity (RV) signal on the order of 10 cm/s. Extreme Precision RV (EPRV) instruments are now sensitive enough to observe signals below this threshold, but stellar surface convection produces RV signals much larger than 10 cm/s [13]. "Convective Blueshift" (CBS) is a net blueshifting of spectral line wings resulting from the convection granulation pattern (warm upflows cover more surface area than cold downflows). CBS measurements were recently obtained for hundreds of stars [30]; a tight cubic relationship is found between the effective temperature and CBS, which may result from the changing size of convective granules. In order to robustly remove CBS from EPRV signals, empirical fits must be tested and validated against theory and nonlinear magnetoconvection simulations.

Convection at the Sun's surface has been studied in exquisite detail in Cartesian simulations which include full radiative transfer (RT) treatments [e.g., 38, 15]. Unfortunately this full RT treatment makes these simulations costly, so studying CBS across the lower main sequence is not feasible. I will develop magnetoconvection simulations with reduced models of RT. Using a computationally efficient but still realistic RT treatment, I will create a simulation suite spanning the lower main sequence and create synthesized observables to compare with existing CBS datasets.

The University of Exeter is deeply involved in the Terra Hunting Experiment (Profs. Naylor & Baraffe and Dr. Haywood), which will survey G and K-type stars with the HARPS III high-resolution spectrograph at the Isaac Newton telescope every night for 10 or more years. This survey will provide extremely precise data on the activity and surface dynamics of the stars, and should start in 2023-2024. Data from this survey will be ready to use to validate my simulations when I arrive at Exeter.

Task 4: I will create fully compressible magnetoconvection simulations in *Dedalus* in a local, Cartesian model of a stellar surface using three different levels of approximation for radiative transfer. I will implement convection under the Eddington tensor approximation [previously tested in *Dedalus* in ref. 10, sct. XI.G], under the approximation of a grey atmosphere with a "realistic" radiative diffusivity [5], and under a simplified diffusion approximation with an idealized radiative diffusivity and an imposed surface cooling. I will test how properties such as the size and flow speed of convective granules vary across these approximations. I will choose the simplest approximation with the highest fidelity to the Eddington tensor solution to use in future CBS simulations.

Task 5: I will create a suite of local simulations of surface convection spanning the lower main sequence. I will synthesize observables of CBS and compare these to observations [30], including those which will be obtained at Exeter from HARPS III. I will work alongside members of the Terra Hunting Experiment to refine CBS prescriptions based on these results.

Deliverable: **The first simulated constraint from 3D MHD simulations on convective blueshift spanning the lower main sequence.**

Timetable Tasks 1-3 are sequential, but can be performed separately from tasks 4-5. Therefore, Focus I & II will occur in parallel with Focus III. Each task will result in at least one peer-reviewed journal article. See Fig. 2 for an expected timetable of these projects.

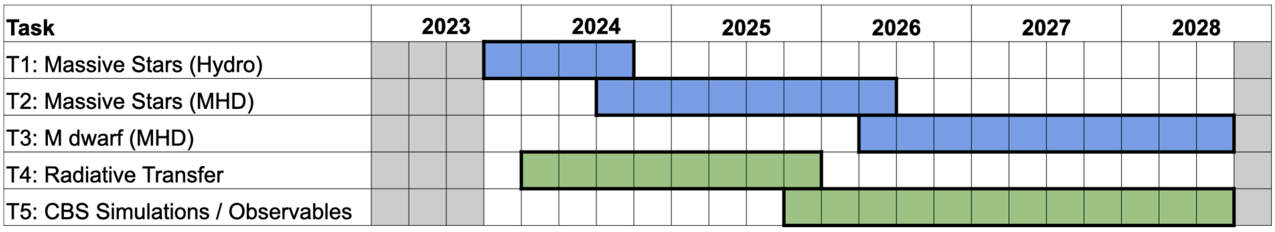

Figure 2: A Gantt chart of the approximate expected timetable for task completion.

Conclusion, Impact, and Outlook I propose to create the first 3D, full-sphere, thermally-equilibrated magnetoconvection simulations of massive stars and M dwarfs. My results will improve stellar evolution models, in turn affecting estimates of the populations of stellar remnants and the ages of stellar clusters. I furthermore will create a suite of local, 3D Cartesian simulations of surface convection spanning the lower main sequence, and these results will improve convective blueshift models and extreme precision radial velocity measurements in the hunt for extrasolar planets. The University of Exeter is the ideal location to pursue these projects thanks to many opportunities for expert collaborations. Beyond research, I look forward to contributing to the vibrant education and public outreach community at Exeter. I look forward to contributing to ongoing initiatives (e.g., *Exoplanet Explorers*, public outreach talks, development of online learning resources), and to experimenting with novel methods of communicating my own research to the public and to differently-abled individuals such as by sonifying results [44].

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