Working group report: Stars and Stellar Evolution

Falk Herwig: contribution on stellar evolution and hydrodynamics

Major progress over past decade

Over the past decade several groups have significantly expanded the capability (and general availability thereof) in stellar evolution and nucleosynthesis modeling. Simulations have enabled many detailed investigations of how nuclear physics uncertainties are propagating through multi-physics simulation codes and impact astronomical observables. This development enables with little additional effort detailed nuclear data impact investigations for a wide range of nuclear production scenarios, thereby providing a critical tool to prioritize nuclear astrophysics experimental effort. Many investigations of the significant impact of many reactions, uncluding the important $^{12}C+^{12}C$, $^{14}N+p$, triple-α and $^{12}C+\alpha$ reactions have been carried out and demonstrate in detail the significant, and sometimes dominant, contribution of nuclear physics uncertainties to the overall uncertainty budget.

One-dimensional stellar evolution simulations are now routine for all phases of the evolution of stars that are at all suitable for spherically symmetric simulations, and internally consistent grids of stellar models and their complete nucleosynthesis are now available. Many individual stars, especially in recent years a larger sample of very metal-poor stars, have been compared in detail with model predictions. Through this work it was possible to verify that the C-enhanced metal-poor stars with enhancements of slow-neutron capture elements are polluted from a former giant star companion that is now a white dwarf.

A lot of effort in stellar evolution has been devoted in the past decade toward calculating models for low-metallicity stars all the way down to the lowest metal contents and even Pop III star abundances (i.e. those stars that formed out of pure BBN material). As a result general insight of nuclear production in the first generations of stars has been developed, to the point where the confrontation of model predictions with observed abundances of metal-poor halo or extra-galactic stars starts to provide intriguing constraints on local implications structure formation models (see cosmology section).

Nucleosynthesis is routinely investigated in stellar mergers, such as progenitors of the unusual R Cr Br class stars, or nuclear production sites in stellar binaries, such as nova and X-ray bursts, and detailed abundance predictions have been shown to agree generally well with observations.

The quantitative interpretation of isotopic ratios from measurements of pre-solar grains has made tremendous progress. This observational access to the nucleosynthesis and mixing processes in interiors of stars and stellar explosions is complementary to astronomical observations and provides extremely powerful constraints for the mixing and nuclear physics of the origin of the elements.

The role of non-standard physics processes, such as rotation and magnetic fields is now understood much better, although a significant uncertainty in this area remains. I has become clear that the mixing effects of rotation in both massive stars

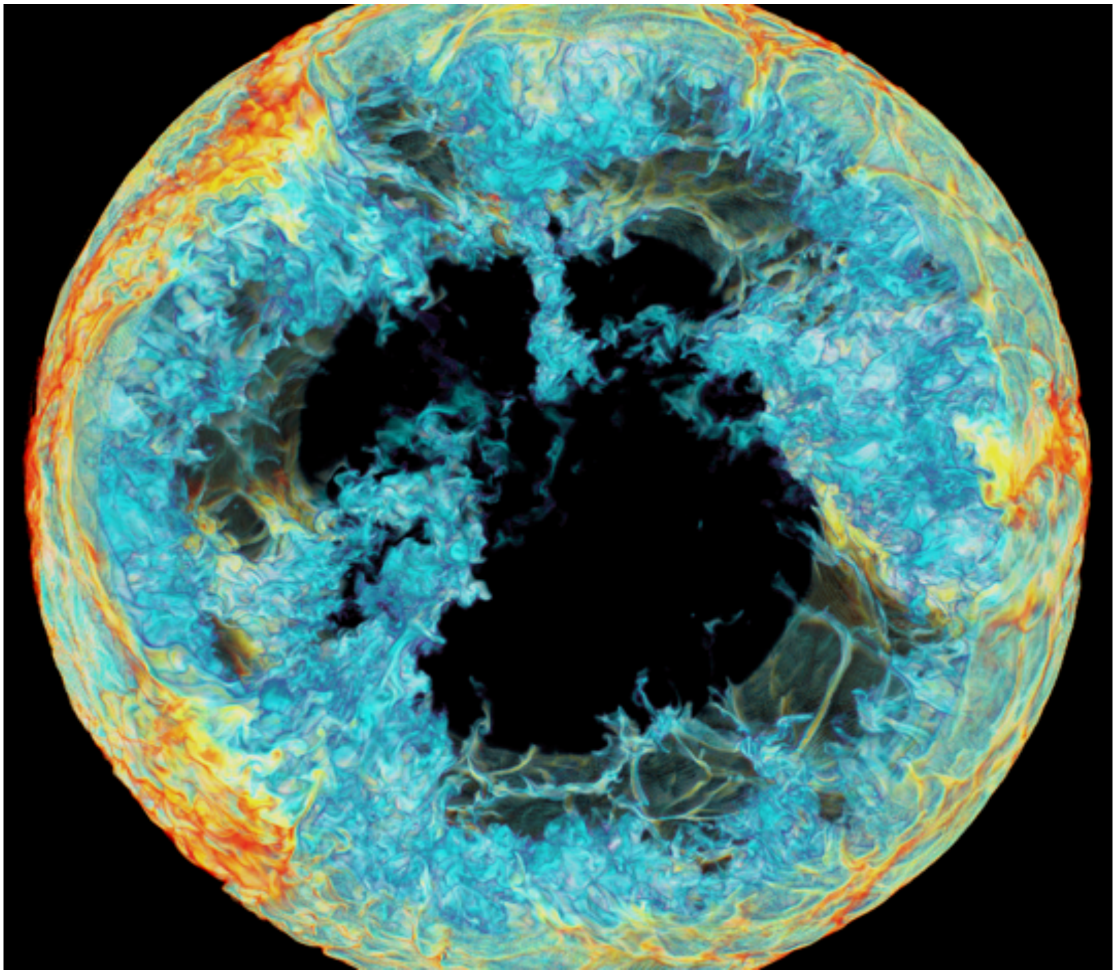

Figure 1: *Visualization of entrainment processes at a convection boundary in a stellar hydrodynamics simulations. Shown is the concentration of H-rich material that is mixed from a stable layer (outside the spherical circumference, not seen) into an underlying Carbon-12 rich convection layer inside a star. The heterogeneous concentration distribution is the result of mixing processes that are critical for the production of the elements in stars. This run was performed on a 768^3 grid over 1.47 million time steps on the WestGrid cluster orcinus (April 2012), running on 2056 cores for a total of 500,000 CPU hours. Credit: Paul Woodward, LCSE – U Minnesota / Falk Herwig, U Victoria.*

as well as AGB stars are likely less important than previously thought. However rotation seems to be playing an important role in binary systems as well as for certain progenitor models of supernova that require fast rotation.

Several groups are now investigating convection and convective mixing in stellar interiors through three-dimensional hydrodynamics simulations (e.g., Figure 1). This new development has only started in earnest in the past decade, and takes full advantage of the substantially increasing computational resources. The simulation-based findings are converging in that the conventional treatment of convection via the mixing-length theory (MLT) in stellar evolution models needs urgently to be updated. In particular, while averaged convective velocities well inside the convective boundary are properly represented by MLT, the important behavior at convective boundaries is poorly described by MLT and this poses significant limitations to further progress toward predictive simulations of the origin of the elements. However, successful proof-of-concept studies have now firmly established that stellar interior convection is accessible through direct three-dimensional simulations.

As a byproduct of several transient-method based exo-planet search missions a significant amount of data for asteroseismology has been collected over the past decade, notably through the CoRoT and KEPLER missions. This data provides another independent avenue to constrain stellar physics for nuclear astrophysics simulations. In this way our understanding of the internal rotation profiles of giant stars and the role of turbulent mixing and diffusion in stars has been significantly improved.

Challenges and open problems

Yield predictions and validation

Over the last decades many important open questions and details of stellar evolution have been investigated and clarified. One of the major goals for the next decade will be to enhance the fidelity, accuracy and completeness of *large, internally consistent yield sets* including stellar evolution (pre-supernova) and explosive supernova contributions. This is required so that such yield sets can be used for *applications in galactic chemical evolution and near-field cosmology*. Initial versions of such data sets have become available in recent years. However, completeness in both covered elements and mass- and metallicity-range, as well as the input physics needs to be further improved.

The computational tools for such large-scale yield calculations are available, and can be used to *systematically explore uncertainties in all contributing areas of input physics*, including in particular the two most important areas - nuclear physics rates and hydrodynamic mixing processes. This capability will ensure that future progress in both areas (see below) can be readily confronted with the increasing body of stellar abundance observations, from the extremely metal poor halo stars that sample the structure and star formation processes in the early Universe, to extra-galactic systems such as dwarf galaxy satellites of the Milky Way which probe chemical evolution in a range of conditions and allow nuclear astrophysics *yield predictions to be used as a diagnostic tool* to address a wide range of open questions relevant to a wide range of astronomers.

Although yield predictions have been improved and will be further refined in the coming decade it will be necessary to establish sound *validation procedures* for yield predictions so that improvements in modeling accuracy can be measured and assessed. Such a validation framework needs to apply simultaneously the constraints from well-defined and orthogonal observational tests that are directly relevant to the various aspects of input physics. The framework would include multi-wavelength stellar observational data from well-understood astronomical sources, as well as isotopic data from grains. The goal would be to test individual physics models, e.g. of nuclear reaction rate sets or mixing physics simultaneously in different stellar environments with a variety of observational tests to allow breaking the degeneracy that most individual constraints are plagued with. Without such a systematic validation effort it is difficult to see how yield predictions based on different uncertain physics assumptions can be evaluated in order to fully support the interpretation of observational data for a more general range of astronomical questions.

The new yield sets need to incorporate progress in the quantitative understanding of *stellar mass loss* made possible through observations and simulations. However, other basic input physics aspects, such as stellar opacities, need to be updated as well. In the latter case, the way abundance mixtures in stars are approximated is outdated and expertise at the national labs could make critical contributions through accurate and flexible microphysics modules that are commensurate with today's computational resources.

Three-dimensional physics of mixing and convective-reactive nucleosynthesis

Major progress in modeling *convection induced mixing* in all its forms during various stages of stellar evolution can be expected to derive from *high-fidelity multi-dimensional simulations* that are now becoming available. Such simulations are tackling the simmering phase in supernova type Ia explosions as well as shell convection zones of C- and O-burning in pre-supernova massive stars and of He-shell flashes in late stages of low- and intermediate mass stars.

The *emerging simulation capability* provides a huge potential to significantly improve the accuracy of stellar models, and provide an indispensible complement to the upcoming new nuclear physics data for nucleosynthesis off the valley of stability. Simulations such as those shown in Figure 1 may be performed on new systems, like Blue Waters, on grids of 2048^3 or even 3072^3 which has been shown to be sufficient to converge key properties of interior convection properties such as mixing at and across convective boundaries. However, fully demonstrating numerical convergence for all applications, and balancing microphysics detail with the need to manage computational cost in resolved hydrodynamic simulations will remain an issue in this decade. But with appropriate effort the basic properties of the stellar interior convection and nuclear burning problem in the late stages of stellar evolution can now be resolved.

Such progress would enable generating more realistic 3D initial models for core-collapse supernova simulations. Another important area for progress would be a thorough investigation of the H-He convective-reactive phases of evolution that are especially prominent in stellar modeling attempts for the lowest metallicity and zero-metallicity stellar generations. In such events protons and primary ^{12}C from a He-burning layer are reacting and releasing energy on the convective time scale of the order of 5 – 60 minutes. Spherically symmetric convection theories (such as the MLT, see above) have been shown to be unreliable under these conditions.

Nucleosynthesis, for example via neutron captures, away from the valley of stability (typically by 3-6 in mass) is predicted for such environments, and much of the nuclear physics – both from the theoretical as well as the experimental side – is poorly or not at all known. Similar nuclear physics data for n-capture rates as well as β-decay rates, both at stellar temperatures are also needed for the important s-process branchings that provide important and detailed probes of many advanced nuclear production sites in the late stages of stellar evolution. New radioactive beam facilities, paired with appropriate theory effort needs to address this nuclear data need. Predictions of such branchings can be combined with isotopic data from pre-solar grains to provide powerful validation scenarios.

Even in standard convection scenarios, assumptions of the presently adopted spherically symmetric convection theory have to be revisited through simulations of stellar hydrodynamics. A critical theory need will be the appropriate connection between three-dimensional modeling results and the global (spherically symmetric) production run capability. The hope is that stellar evolution simulations with such enhanced mixing models will provide more reliable yield predictions for nuclear astrophysics.

Super-AGB stars and the lowest-mass supernova progenitors

While the evolution of low- and intermediate mass stars will remain a focus area of stellar evolution research the mass range between 7 and 10Msun needs to receive the most attention now. Some recent investigations have addressed the shell burning properties of super-AGB stars and shown that most uncertainties are again due to a lack of understanding of convection and mass loss. The transition from the initial mass range that form ONe white dwarfs to the initial masses that provide the progenitors of the lowest-mass supernova remains a poorly charted territory. Basic properties of the evolution of convective shells inside electron-degenerate cores, the interaction of turbulence, unusual nuclear reaction chains under extreme conditions and neutrino losses form a delicate balance that does not allow much room for error. This regime is particularly important as the initial-mass function favors lower-mass supernova progenitors in numbers. It has been suspected to be the nuclear production site for a number of exotic processes, such as the r process or other high neutron-density processes associated with convective-reactive regimes, that may play a role in some of the poorly understood observational phenomena of the metal-poor universe, such as the C-enhanced metal poor stars with s and r process signature. Light-curves from supernova from this mass range may be constraint by time-domain surveys and provide pivotal constraints for the underlying physics responsible for the evolutionary fate of stars in this mass range.

Binaries and supernova type Ia progenitors

Most stars are binaries and many will at some point in their lives interact in one way or another with their companion. These interactions, such as tidal interactions, the common envelope phase, mass transfer and double degenerate mergers involve non-spherically symmetric hydrodynamic processes that pose significant challenges to our understanding. Binary evolution may be the most important source of rapidly rotating stars, and despite promising progress in recent years the quantitative understanding of the detailed evolution, nucleosynthesis and final death of such interacting binaries remains a challenge. Our limits of binary stellar evolution manifests itself in the still unknown progenitor evolution of supernova type Ia, which in all models requires some kind of binary interaction. For the single-degenerate scenario the physics of accreting compact objects needs to be better understood, including the interaction of the accreting stars with the mass donor companion star. For the double-degenerate path the properties of the pre- and post-dynamic merger phase needs to be investigated. In both scenarios the progenitor models need to be based on realistic progenitor evolution with the same physics updates required as discussed previously for yield predictions. Key reaction rates, such as the $^{12}C+^{12}C$ rate will effect the model predictions of the progenitor populations. Also, for both scenarios better observational constraints for progenitor evolution scenarios are needed.