THE TURBULENT ORIGIN OF THE ELEMENTS: DYNAMICAL/CHEMICAL EVOLUTION AND EXPLOSIONS OF MASSIVE STARS AND IMPLICATIONS FOR ASTROBIOLOGY.
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Introduction: Arizona State University's (ASU) team of the NASA Astrobiology Institute investigates the occurrence and diversity of habitable environments on the basis of availability of certain "bio-essential" chemical elements. With the goal of quantifying element production by fusion in massive stars, this study uses the TYCHO stellar evolution code [1] to evolve model stars of 0.5-100 solar masses, with emphasis on generating a suite of supernova progenitors from stars with initial masses 8-100 $M_{\odot}$. Sets of model stars of different metallicities (relative to solar [2, 3]) are evolved from pre-main-sequence to core collapse, and the elemental abundances in their enclosed masses are calculated. Later, a one-dimensional explosion code and the three-dimensional SNSPH smoothed-particle hydrodynamics code [4] will be applied to these models to yield possible elemental abundances and distributions in asymmetric supernova ejecta. Post-processing will generate yields for 524-3300 isotopes, depending on the conditions of the nuclear burning. These new yields and stellar evolution tracts will be the first to incorporate new, predictive physical descriptions of convection and mixing.

TYCHO uses a completely new, more accurate, non-local description of convection. Its approach is based upon theoretical and experimental hydrodynamics developed over decades in the atmospheric and hydrological science communities and on multi-D simulations of stellar interiors. It is not merely a patch to the venerable mixing length theory (MLT). In particular, convective average velocities are calculated by integration of buoyancy forces, giving the kinetic energy flux of convection [5]. Fluctuations are modeled with a Reynolds decomposition on kinetic energy and internal energy in a modified Lagrangian formalism, giving enthalpy flux of convection. The extent of convection is determined by evaluating the bulk Richardson number instead of thermodynamic criteria. This allows regions near the boundary that are hydrodynamically unstable to mix, resulting in larger convective zones. Thermodynamic criteria are suitable only for determining the onset of convection, not the extent of an established convection zone [5]. The radial scale of mixing is a function of the depth of the convection zone. In analogy to mixing length theory, the mixing length is set by the size of the unstable region, and is not a free parameter. The kinetic properties of the convective flow are used to calculate a spectrum and flux of g-mode waves at convective boundaries. The gradient Richardson number evaluates stability of stratification against shear velocities in the star regardless of the source of the fluid flow. The bulk Richardson number determines how far turbulent mixing progresses when the stability drops below the critical gradient Richardson number. Critical regions are hydrodynamically unstable and undergo turbulent mixing. Subcritical regions undergo slow circulation and mixing on a thermal timescale. This allows a unified fluid flow treatment of rotation, internal waves, and entrainment at convective boundaries, including cross terms, that describe transport of energy, chemical species, and angular momentum.

Evaluation of the model supernovae end-products may yield correlations in elemental ratios, potentially highlighting observable proxies for "bio-essential" elements in the search for habitable stellar systems in the solar neighborhood. Analyses of asymmetric 3-D explosion calculations can inform studies of the incorporation of expelled elements into other stars within a cluster, including planetary bodies forming around them.

The results of these calculations will compose a library providing these model stars' evolutionary tracks, internal structures through time, mass-loss histories, and elemental compositions throughout their evolution. These libraries are intended for the backbone of an online resource for both researchers in stellar evolution and nuclear physics, and for the general public interested in astrobiology and the formation of the chemical elements by stellar fusion.

TYCHO model set: The TYCHO code is used to evolve model stars of 0.5-100 $M_{\odot}$ to core collapse; the mass grid spacing is $\Delta M = 0.1\ M_{\odot}$ from 0.5-2 $M_{\odot}$, $\Delta M = 0.25\ M_{\odot}$ from 2-5 $M_{\odot}$, $\Delta M = 0.5\ M_{\odot}$ from 5-20 $M_{\odot}$, $\Delta M = 1\ M_{\odot}$ from 20-30 $M_{\odot}$, $\Delta M = 2\ M_{\odot}$ from 30-50 $M_{\odot}$, and $\Delta M = 5\ M_{\odot}$ from 50-100 $M_{\odot}$, for a total of 88 model stars (in a single set of a prescribed metallicity, beginning with solar). The first set of models does not include rotation.

Stellar Evolution, Nucleosynthesis, and Supernova Progenitor Library: A sample of preliminary results of the first set of TYCHO runs are shown in Figures 1 and 2; more complete results will be presented in an online database. In consructing the public library much emphasis is on visualizations of the results; for example one may view a movie of the evolution of a star in temperature and luminosity alongside a map of its internal structure, with explanations of active processes at important evolutionary stages, and graphical representations of the elemental composition (of the hole star or specific regions within). This library will be later expanded to include the results of the supernova simulations, with visualizations of the ejecta, abundance tables, and explanations of the predictive strength of asymmetric 3-D over 1-D calculations.

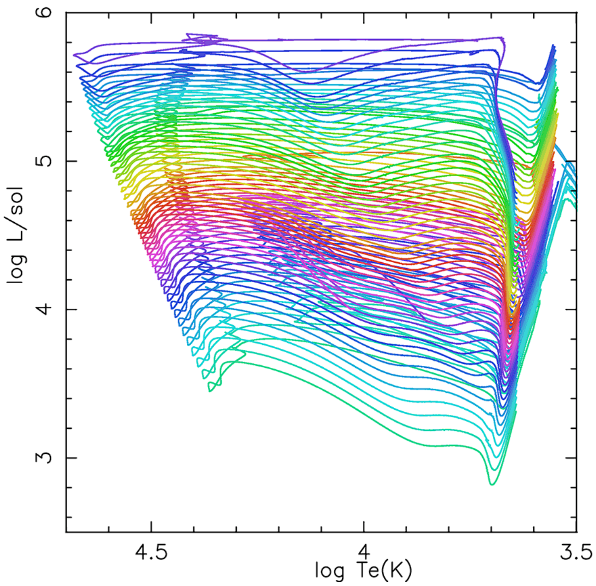

Figure 1: Effective temperature-luminosity plots of 47 model stars evolved in TYCHO [1], with initial masses from 8 $M_{\odot}$ (bottom) to 60 $M_{\odot}$ (top).

References: [1] Young P. A. and Arnett D., (2005) *ApJ*, *618*, 908. [2] Lodders K., (2003) *ApJ*, *591*, 1220. [3] Grevesse N. *et al.*, (2007) *SpSciRev*, *130*, 105. [4] Fryer C. L. *et al.*, (2006) *ApJ*, *643*, 292. [5] Arnett D. *et al.*, (2009) *ApJ*, *690*, 1715.

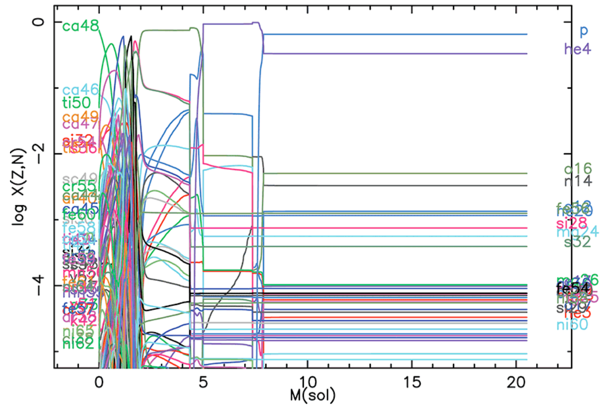

Figure 2: Chemical composition ($\log_{10}$ abundance *vs.* enclosed mass) of a 24 $M_{\odot}$ star evolved to core collapse in TYCHO [1]. Note both the ~ 3.5 $M_{\odot}$ lost by this point, and the core of Fe-peak nuclei (much of which has been photodisintegrated to produce a wealth of ^{48}Ca).