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Stellar Evolution Differently

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ABSTRACT
Stellar evolution differently ..

Key words: turbulence – mixing – nuclear burning – stellar evolution

1 INTRODUCTION

Emerging evidence for neglected physics important for stellar evolution based on 3D hydrodynamic compressible simulations of convective-reactive events force us to reconsider our approach to model structure of stars. It looks like there is a whole zoo of missing stellar physics not included in our steller evolutionary calculations, namely (i) explicit background time-dependency (ii) non-local effects and (iii) compressibility effects.

To include all physics present in convective-reactive flow in stars, one has to be able to cope with the following set of hydrodynamic stellar structure equations, where $\mathcal{T}_m, \mathcal{T}_u, \mathcal{T}_\epsilon, \mathcal{T}_T$: describe background structure; $\mathcal{T}_i, \mathcal{T}_{f_i}$: describe nuclear burning and transport of element i; and $\mathcal{T}_R, \mathcal{T}_{\sigma_T}, \mathcal{T}_{f_T}$: give correct size of convection zone arising naturally from solution (Biferale et al. 2011).

$$\mathcal{T}_m = -\nabla_r f_\rho + 3\overline{\rho}\widetilde{u}_r/r + (f_\rho/\overline{\rho})\partial_r\overline{\rho} - \mathcal{C}_m \tag{1}$$

$$\mathcal{T}_u = -\nabla_r \widetilde{R} + \overline{\rho}\widetilde{g} - \partial_r\overline{P} - \overline{G}_r^M - \overline{\rho}\widetilde{u}_r\partial_r\widetilde{u}_r \tag{2}$$

$$(1/\mathcal{S})\mathcal{T}_\epsilon = -\nabla_r(f_i + f_{th} + f_K + f_p) + \overline{\rho}\widetilde{\epsilon}_{\rm nuc} - \mathcal{C}_\epsilon^b + W_b - \widetilde{R}_{ir}\partial_r\widetilde{u}_i + \overline{\rho}\widetilde{D}_t\widetilde{u}_i\widetilde{u}_i/2 - \partial_r\widetilde{L} + (\widetilde{\epsilon}_t/\mathcal{S})\,\partial_r 4\pi r^2\overline{\rho}\widetilde{u}_r \tag{3}$$

$$\mathcal{T}_T = -\nabla_r f_T + \mathcal{C}_T^b + \mathcal{C}_T^t + \epsilon_{nuc}/c_v + \mathcal{H}_T^T - \overline{u}_r\partial_r\overline{T} \tag{4}$$

$$\mathcal{T}_i = -\nabla_r f_i + \overline{\rho}\widetilde{\dot{X}}_i^{\rm nuc} - \overline{\rho}\widetilde{u}_r\partial_r\widetilde{X}_i \tag{5}$$

$$\mathcal{T}_{f_i} = -\nabla_r f_i^r - f_i\partial_r\widetilde{u}_r - \widetilde{R}_{rr}\partial_r\widetilde{X}_i - \mathcal{P}_{f_i} + \mathcal{A}_{f_i}^{\rm nuc} + \mathcal{G}_i - \overline{\rho}\widetilde{u}_r\partial_r f_i/\overline{\rho} \tag{6}$$

$$\mathcal{T}_R = -\nabla_r(2f_k^r + 2f_p) + 2W_b - 2\widetilde{R}_{rr}\partial_r\widetilde{u}_r + \mathcal{C}_R^t + 2\mathcal{G}_k^r - \overline{\rho}\widetilde{u}_r\partial_r\widetilde{u_r''u_r''} + \varepsilon \tag{7}$$

$$\mathcal{T}_{\sigma_T} = -\nabla_r f_{\sigma_T} - \mathcal{C}_\sigma^o - 2f_T\partial_r\overline{T} - \mathcal{C}_{\sigma_T}^w + \mathcal{C}_{\sigma_T}^e + \mathcal{H}_{\sigma_T}^T + \mathcal{A}_{\sigma_T}^{\rm nuc} - \widetilde{u}_r\partial_r\sigma_T \tag{8}$$

$$\mathcal{T}_{f_T} = -\nabla_r f_T^r - f_T\partial_r\overline{u}_r - \overline{u_r'u_r''}\partial_r\overline{T} - \mathcal{P}_{f_T} - \mathcal{C}_{f_T}^o - \mathcal{C}_{f_T}^w - \mathcal{C}_{f_T}^t + \mathcal{C}_{f_T}^s + \mathcal{A}_{f_T}^{\rm nuc} + \mathcal{H}_{f_T}^T - \widetilde{u}_r\partial_r f_T + \mathcal{G}_T \tag{9}$$

$$M = \int \rho dV = \int \frac{m}{V} dV = m(r)\ln V(r) \quad ??(check) \tag{10}$$

this is introduction, test citation Sytine et al. (2000)

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Table 1. Definitions:

$R = \overline{\rho}\widetilde{u''_r u''_r}$	$\mathcal{C}_m = \overline{\rho}\overline{d}$	$\mathcal{H}^T_\sigma = \overline{(2/\rho c_v)T'\nabla \cdot F_{th}}$
$f_i = \overline{\rho}\widetilde{X''_i u''_r}$	$\mathcal{C}^b_\epsilon = \overline{Pd}$	$\mathcal{C}^o_{f_T} = (\Gamma_3 - 1)(\overline{T}\ \overline{u'_r d''})$
$\mathcal{T}_m = \partial_t \overline{m}$	$\mathcal{C}^b_T = (1-\Gamma_3)\overline{T}\ \overline{d}$	$\mathcal{C}^w_{f_T} = (\Gamma_3 - 1)(\widetilde{d}\ \overline{u'_r T'})$
$\mathcal{T}_u = \overline{\rho}\partial_t \widetilde{u}_r$	$\mathcal{C}^t_T = (2-\Gamma_3)\overline{T'd'}$	$\mathcal{C}^t_{f_T} = (\Gamma_3 - 1)(\overline{u'_r T' d''})$
$\mathcal{T}_\epsilon = \overline{\rho}\partial_t \widetilde{\epsilon}_t$	$\mathcal{C}^t_R = 2\overline{P'\nabla_r u''_r}$	$\mathcal{C}^s_{f_T} = \overline{T' u'_r d''}$
$\mathcal{T}_T = \partial_t \overline{T}$	$f_{\sigma_T} = \overline{(T'T'u''_r)}$	$\mathcal{C}^T_{f_T} = \overline{u'_r \nabla \cdot F_{th}/\rho c_v}$
$\mathcal{T}_i = \overline{\rho}\partial_t \widetilde{X}_i$	$f_T = \overline{T'u''_r}$	$\mathcal{A}^{\mathrm{nuc}}_{f_T} = \overline{2T'\epsilon_{\mathrm{nuc}}/c_v}$
$\mathcal{T}_{f_i} = \overline{\rho}\partial_t (f_i/\overline{\rho})$	$\sigma_T = \overline{T'T'}$	$\mathcal{A}^{\mathrm{nuc}}_{\sigma_T} = \overline{u'_r \epsilon_{\mathrm{nuc}}/c_v}$
$\mathcal{T}_R = \overline{\rho}\partial_t \widetilde{u''_r u''_r}$	$\mathcal{C}^o_\sigma = 2(\Gamma_3 - 1)\overline{T}\ \overline{T'd''}$	$\mathcal{A}^{\mathrm{nuc}}_{f_i} = \overline{u''_r \rho \dot{X}^{\mathrm{nuc}}_i}$
$\mathcal{T}_{\sigma_T} = \partial_t \overline{T'T'}$	$\mathcal{C}^w_\sigma = 2(\Gamma_3 - 1)\widetilde{d}\sigma_T$	$\mathcal{P}_{f_T} = \overline{T'\partial_r P/\rho}$
$\mathcal{T}_{f_T} = \partial_t \overline{T'u'_r}$	$\mathcal{C}^e_\sigma = (3 - 2\Gamma_3)\overline{T'T'd''}$	$\mathcal{P}_{f_i} = \overline{X''_i \partial_r P}$
$d = \nabla \cdot \mathbf{u}$	$\mathcal{H}^T_T = (1/\rho c_v)\ \nabla \cdot F_{th}$	$\mathcal{S} = 4\pi r^2$

Table 2. Definitions:

ρ density	g_r radial gravitational acceleration
$m = \rho V = \rho \frac{4}{3}\pi r^3$ mass	$M = \int \rho(r) dV = \int \rho(r) 4\pi r^2 dr$ integrated mass
T temperature	$\mathcal{S} = \rho \epsilon_{\mathrm{nuc}}(q)$ nuclear energy production (cooling function)
P pressure	$\tau_{ij} = 2\mu S_{ij}$ viscous stress tensor (μ kinematic viscosity)
u_r, u_θ, u_ϕ velocity components	$S_{ij} = (1/2)(\partial_i u_j + \partial_j u_i)$ strain rate
$\mathbf{u} = u(u_r, u_\theta, u_\phi)$ velocity	$\widetilde{R}_{ij} = \overline{\rho}\widetilde{u''_i u''_j}$ Reynolds stress tensor

(11)

Table 3. Definitions:

$$
\begin{array}{l}
R = \overline{\rho}\widetilde{u''_r u''_r} \\
f_i = \overline{\rho}\widetilde{X''_i u''_r} \\
\mathcal{T}_m = \partial_t \overline{m} \\
\mathcal{T}_u = \overline{\rho}\partial_t \widetilde{u}_r \\
\mathcal{T}_\epsilon = \overline{\rho}\partial_t \widetilde{\epsilon}_t \\
\mathcal{T}_T = \partial_t \overline{T} \\
\mathcal{T}_i = \overline{\rho}\partial_t \widetilde{X}_i \\
\mathcal{T}_{f_i} = \overline{\rho}\partial_t (f_i/\overline{\rho}) \\
\mathcal{T}_R = \overline{\rho}\partial_t \widetilde{u''_r u''_r} \\
\mathcal{T}_{\sigma_T} = \partial_t \overline{T'T'} \\
\mathcal{T}_{f_T} = \partial_t \overline{T'u'_r} \\
\mathcal{S} = 4\pi r^2 \\
\mathcal{C}_m = \overline{\rho}\overline{d} \\
\mathcal{C}^b_\epsilon = \overline{Pd} \\
\mathcal{C}^b_T = (1-\Gamma_3)\overline{T}\ \overline{d} \\
\mathcal{C}^t_T = (2-\Gamma_3)\overline{T'd'} \\
\mathcal{C}^t_R = 2\overline{P'\nabla_r u''_r} \\
f_{\sigma_T} = \overline{(T'T'u''_r)} \\
f_T = \overline{T'u''_r} \\
\sigma_T = \overline{T'T'} \\
\mathcal{C}^o_\sigma = 2(\Gamma_3-1)\overline{T}\ \overline{T'd''} \\
\mathcal{C}^w_\sigma = 2(\Gamma_3-1)\widetilde{d}\sigma_T \\
\mathcal{C}^e_\sigma(3-2\Gamma_3)\overline{T'T'd''} \\
\mathcal{H}^T_T = (1/\rho c_v)\ \nabla\cdot F_{th} \\
\mathcal{H}^T_\sigma\overline{(2/\rho c_v)T'\nabla\cdot F_{th}} \\
\mathcal{C}^o_{f_T} = (\Gamma_3-1)(\overline{T}\ \overline{u'_r d''}) \\
\mathcal{C}^w_{f_T} = (\Gamma_3-1)(\widetilde{d}\ \overline{u'_r T'}) \\
\mathcal{C}^t_{f_T} = (\Gamma_3-1)(\overline{u'_r T'd''}) \\
\mathcal{C}^s_{f_T} = \overline{T'u'_r d''} \\
\mathcal{C}^T_{f_T} = \overline{u'_r\nabla\cdot F_{th}/\rho c_v} \\
\mathcal{A}^{\mathrm{nuc}}_{f_T} = \overline{2T'\epsilon_{\mathrm{nuc}}/c_v} \\
\mathcal{A}^{\mathrm{nuc}}_{\sigma_T} = \overline{u'_r\epsilon_{\mathrm{nuc}}/c_v} \\
\mathcal{A}^{\mathrm{nuc}}_{f_i} = \overline{u''_r\rho\dot{X}^{\mathrm{nuc}}_i} \\
\mathcal{P}_{f_T} = \overline{T'\partial_r P/\rho} \\
\mathcal{P}_{f_i} = \overline{X''_i\partial_r P}
\end{array}
\tag{12}
$$