

Cesam2k20 : un futur code communautaire d'évolution stellaire ?

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Community numerical code

Critères :

1. **Scientific interest** : interest outside the original team of developers, over a long period of time.
2. **Community-based development** : the dev. team must sustain a double community of developers and users (workshops, dev. working days, ...).
3. **User/Dev.-friendly** : version-control, documentation, support, ...
4. **Simulation quality/data accessibility** : Open-source, test-cases, public comparison with other codes, database with precomputed models.

(source : Charte des outils nationaux labellisés par l'INSU, sept. 2022.)

→ **Cesam2k20 (and ESTER) was identified by the PNPS as a potential community code.**

Cesam2k20? Cesam2k++? Cesam#@\$!!

- **CESAM** : *Code d'Evolution Stellaire, Adaptatif et Modulaire*. Originally developed by Pierre Morel (OCA) à partir de 1989. [Morel+1997](#);
- **CESAM2k** : CESAM of the 2000s. Modernization in Fortran 90 (P. Morel, B. Pichon, and many others!); [Morel&Lebreton+2008](#);
- **CESTAM** : T = Transport. Implementation of angular momentum transport by J. P. C. Marques [Marques+2013](#);
- **Cesam2k20** : Most recent version. [Manchon, in prep](#); [Deal, in prep](#).
Devs : M. Deal, Y. Lebreton, J. P. C. Marques, L. Manchon.
Selected to compute PLATO's 1st grid of stellar models.
Identified by the PNPS as a potential community code.
→ 1st public release in dec. 2023 :

Website



<https://www.ias.u-psud.fr/cesam2k20>

Public repository



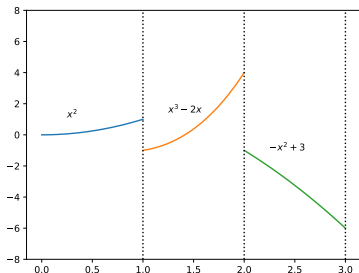
https://git.ias.u-psud.fr/joao.marques/cesam2k20_releases

A modular stellar evolution code

- Two layers :
 - Numerical;
 - Physical.
- Not necessary to know the numerical aspects to implement new physical ingredients :
 - Equation of state;
 - Opacity;
 - Nuclear reaction rates;
 - Diffusion coefficients;
 - Mass loss/accretion rates;
 - Magnetic braking laws;
 - Prescriptions for convection/overshoot;
 - and many others!

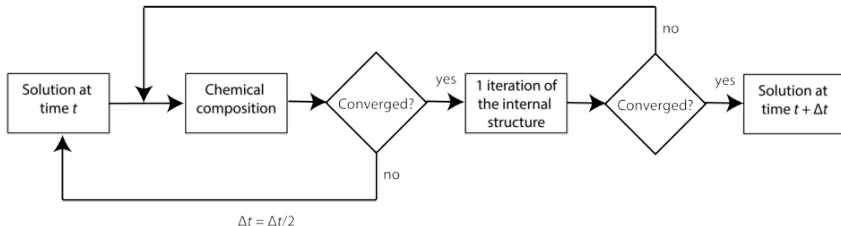
Numerical methods

- Unknowns are represented as order m piecewise polynomial functions.
used for structure, chemical composition, angular velocity, etc.
- Possible to set the degree of discontinuity at break-points.
- piecewise polynomial functions are projected on a local basis of normalized -Splines.



Cesam2k20 flowchart

- Two problems solved separately : internal structure and chemical composition (possibly 3rd problem : rotation);
- Existence and location of convective zones must be known before.



Test stellar models :

Chemical mixing in low mass stars

I. Rotation against atomic diffusion including radiative acceleration

M. Deal^{1,2}, M.-J. Goupil², J. P. Marques³, D. R. Reese², and Y. Lebreton^{4,2}

HOW ACCURATE ARE STELLAR AGES BASED ON STELLAR MODELS?

I. THE IMPACT OF STELLAR MODELS UNCERTAINTIES

Y. Lebreton¹, M.J. Goupil² and J. Montalbán³

Seismic diagnostics for transport of angular momentum in stars

I. Rotational splittings from the pre-main sequence to the red-giant branch

J. P. Marques^{1,2}, M. J. Goupil², Y. Lebreton^{3,4}, S. Talon⁵, A. Palacios⁶, K. Belkacem², R.-M. Ouazzani^{7,2}, B. Mosser², A. Moya⁸, P. Morel⁹, B. Pichon⁹, S. Mathis^{10,2}, J.-P. Zahn¹¹, S. Turck-Chièze¹⁰, and P. A. P. Nghiem¹⁰

Possible usage of Cesam2k20

Improve seismic diagnostics :

Properties of the ionisation glitch

I. Modelling the ionisation region

Pierre S. Houdayer¹, Daniel R. Reese¹, Marie-Jo Goupil¹, and Yveline Lebreton^{1,2}

Modelling the asymmetries of the Sun's radial p-mode line profiles

J. Philidet¹, K. Belkacem¹, R. Samadi¹, C. Barban¹, and H.-G. Ludwig^{2,3}

Influence of metallicity on the near-surface effect on oscillation frequencies

L. Manchon^{1,2*}, K. Belkacem², R. Samadi², T. Sonoi^{2,3}, J. P. C. Marques¹, H.-G. Ludwig^{4,5}, and E. Caffau⁵

Possible usage of Cesam2k20

Model stellar systems :

Modeling of two *CoRoT* solar analogues constrained by seismic and spectroscopic analysis

M. Castro^{1,2,7}, F. Baudin², O. Benomar^{3,4}, R. Samadi⁵, T. Morel⁶, C. Barban⁵, J. D. do Nascimento⁹, Y. Lebreton^{5,8}, P. Boumier², J. P. Marques² and J. S. da Costa⁹

From the stellar properties of HD 219134 to the internal compositions of its transiting exoplanets

R. Ligi¹, C. Dorn², A. Crida^{3,4}, Y. Lebreton^{5,6}, O. Creevey³, F. Borsa¹, D. Mourard³, N. Nardetto³, I. Tallon-Bosc⁷, F. Morand³, and E. Poretti¹

J. P. Marques^{1,2}, M. J. Goupil^{2,3}, R. Samadi², T. Morel⁶, S. Talon⁵, A. Palacios⁶, K. Belkacem², R.-M. Ouazzani^{7,2}, B. Mosser², A. Miglio⁴, P. Morel⁹, B. Pichon⁹, S. Mathis^{10,2}, J.-P. Zahn¹¹, S. Turck-Chièze¹⁰, and P. A. P. Nghiem¹⁰

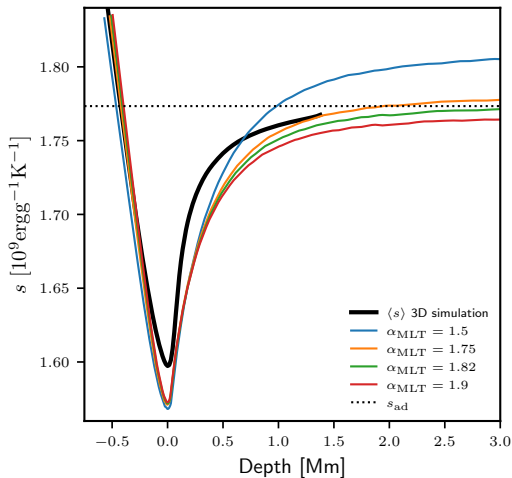
L. Manchon¹⁰

What's new since CESTAM (2013)?

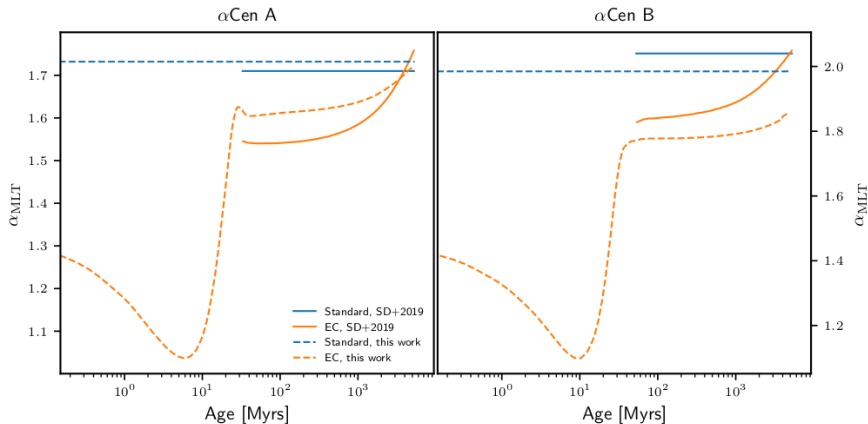
(text in blue : implementation done in the last 2 years)

- Opacity tables for new solar chemical composition (e.g. AAG21);
 - Method of Gabriel+2014 for conv. zones limit determination;
 - Prescriptions for time-dependent α_{conv} / entropy calibration;
 - Improvement of atomic diffusion with radiative accelerations;
 - New prescriptions for turbulent diffusion;
 - 2D structure of rotating stars;
 - Angular momentum transport in 2D (in progress);
 - Moment transport by mixed modes;
 - $T(\tau)$ relations : Vernazza+1983, Krishna-Swamy, Ball+2021;
 - Mass loss prescriptions : Rosenfield+2014, Schroöder & Cuntz's (2005), and many more;
- Manchon et al. (in prep.).

Entropy-calibrated modelling

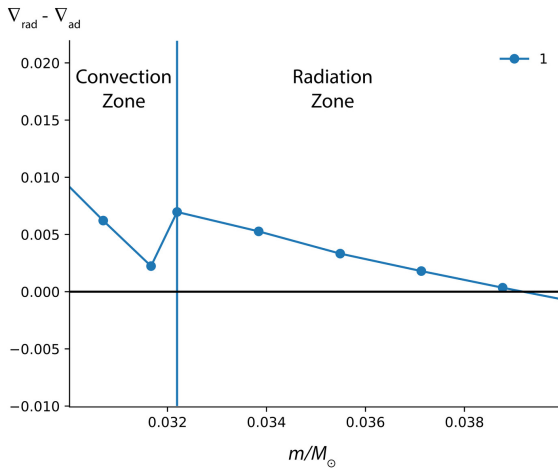


Entropy-calibrated modelling

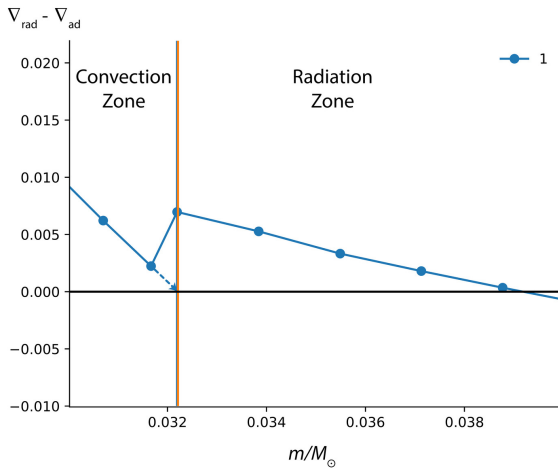


Manchon et al. (subm.)

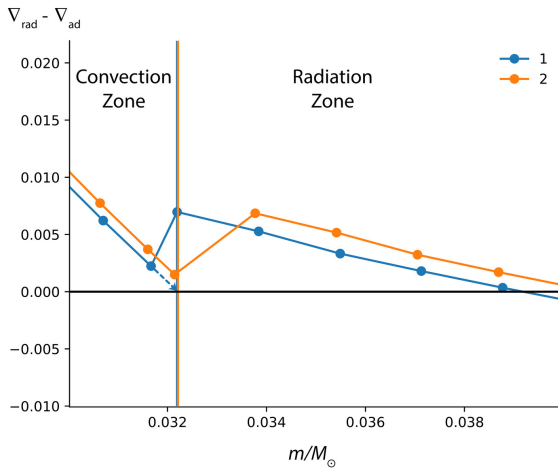
Limites des zones convectives – Gabriel+2014



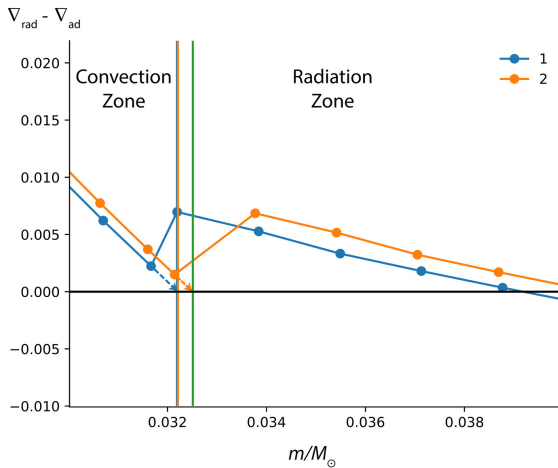
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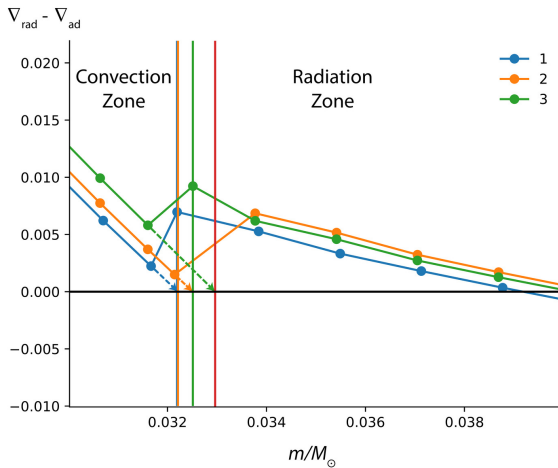
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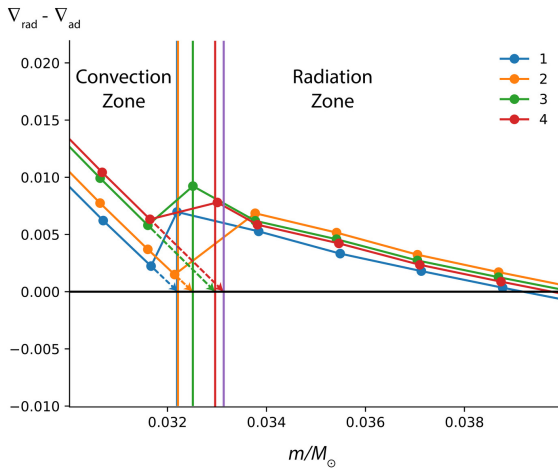
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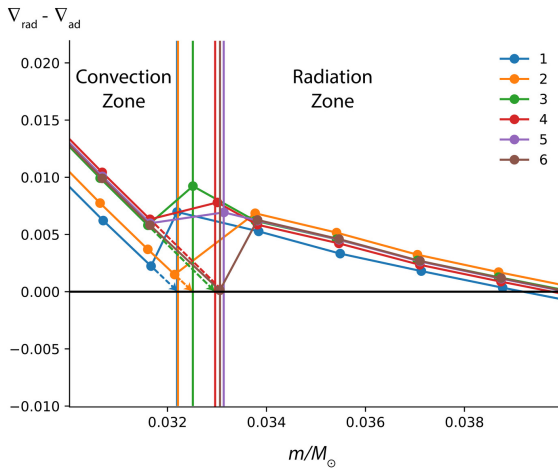
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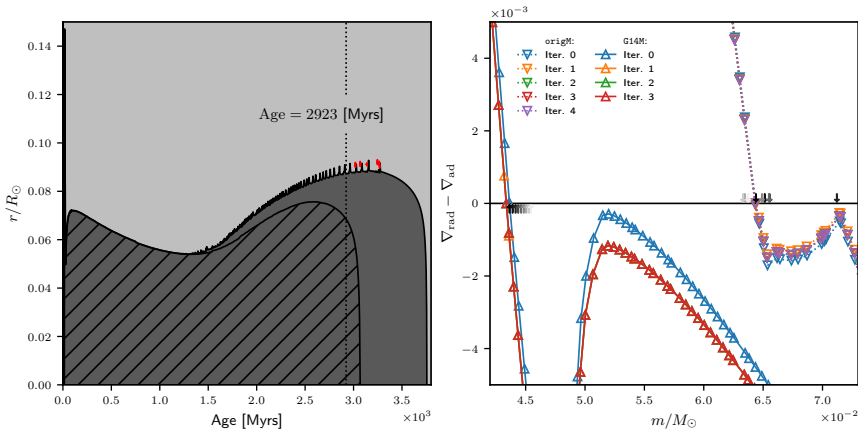
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Limites des zones convectives – Gabriel+2014



Limites des zones convectives – Gabriel+2014



Turbulent and atomic diffusion with radiative acc.

Deal+2018 : in absence of g_{rad} , all elements (except H_1) migrate toward the center due to gravitational settling. With g_{rad} , this effect is reduced, even overcame for Al and Fe.

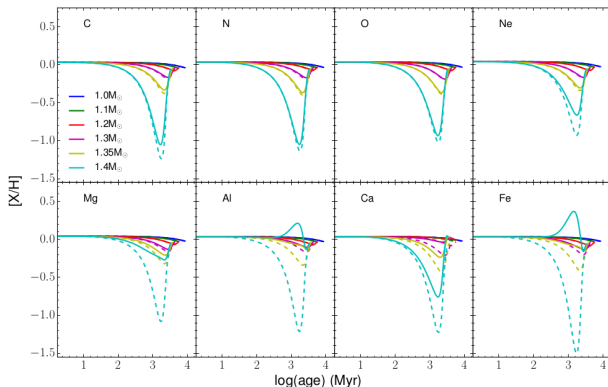


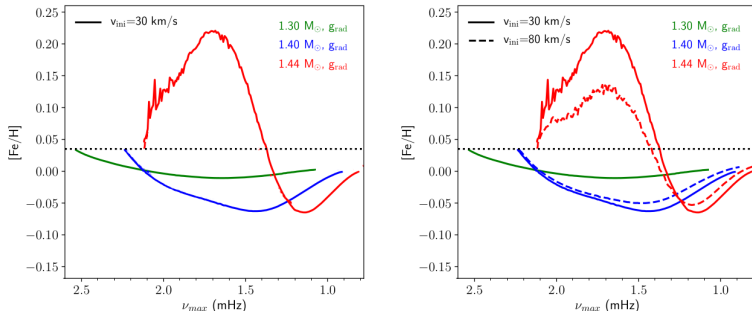
Fig. 3. Evolution of surface abundances ($[X/H]$ calculated as in Eq. 4) with time for the eight elements in grid 2 at solar metallicity. The solid and dashed curves respectively represent models with and without g_{rad} .

→ here, no other transport mechanisms than gravitational settling and g_{rad} are included.

Turbulent and atomic diffusion with radiative acc.

Deal+2020 : Interaction radiative diffusion/rotation.

Rotation competes with radiative accelerations depending on the mass. In low mass stars, conv. envelope is thick and angular momentum is efficiently extracted by winds, which induces strong mixing and unrealistic chemical depletion due to atomic diffusion. As mass increases, efficiency of rotation-induced transport decreases.

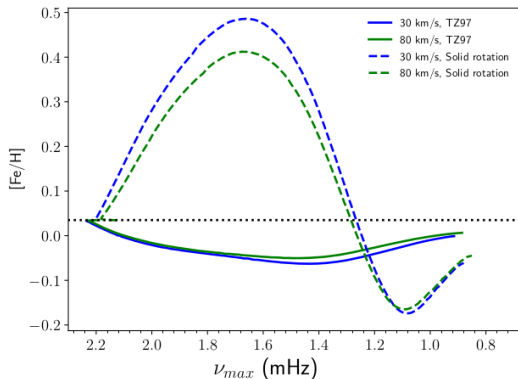


→ in this case, angular momentum transport is underestimated.

Turbulent and atomic diffusion with radiative acc.

Deal+2020 : Interaction atomic diffusion/rotation.

Angular momentum transport (AMT) is underestimated and the "true" evolution of surface element should be somewhere between what we obtain assuming solid rotation, and with classical AMT.



Next developments in Cesam2k20

Physics :

- Evolved phases : **pass helium flash**;
- Transport mechanisms : additional angular momentum transport mechanisms (**Tayler-Spruit**, IGW,...), **finalize 2D AMT**, **turbulent diffusion in convection zone**, ...;
- More realistic envelopes : account for turbulent pressure, improve convection formalisms (**rotation**, **magnetic fields**, etc.), ...;
- Toward low mass stars : need a realistic EoS.
- Toward high mass stars : need better atmosphere.

Numerics :

- Radiative accelerations on GPUs;
- General optimization of the code.

⇒ Engineer for 1 yr!

Can Cesam2k20 be a community code?

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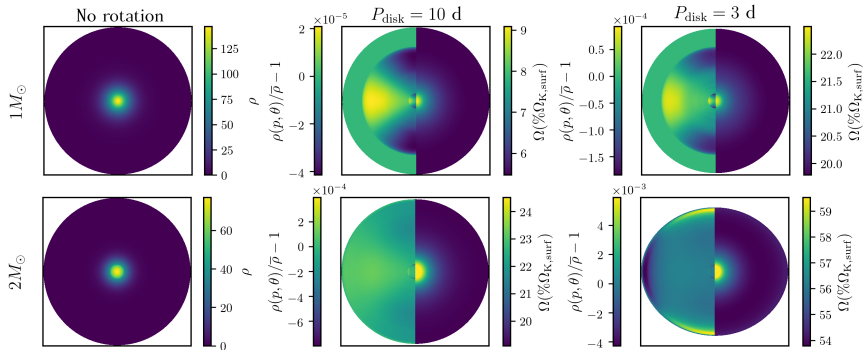


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Merci!

Angular momentum transport in 2D

Deformation due to centrifugal acc. :



Angular momentum transport in 2D : still a work in progress.

1st PLATO grid

- Cesam2k20 selected to compute 1st PLATO grid of stellar models among 2 other codes : GARSTEC and CLES;
- Structural and seismic tests;
- The Physics of the 1st grid :
 - Solar mixture : AAG21 or Magg+22, other?;
 - Atomic diffusion (Michaud&Proffitt);
 - Atmosphere : Vernazza+83;
 - Entropy-calibrated MLT (Spada+18,19,21; [Manchon et al., subm.](#);
 - Overshoot.
- Parameter space :
 - 5 parameters : mass, Y , $[\text{Fe}/\text{H}]$, $[\alpha/\text{H}]$ overshoot;
 - At least 50000 tracks;