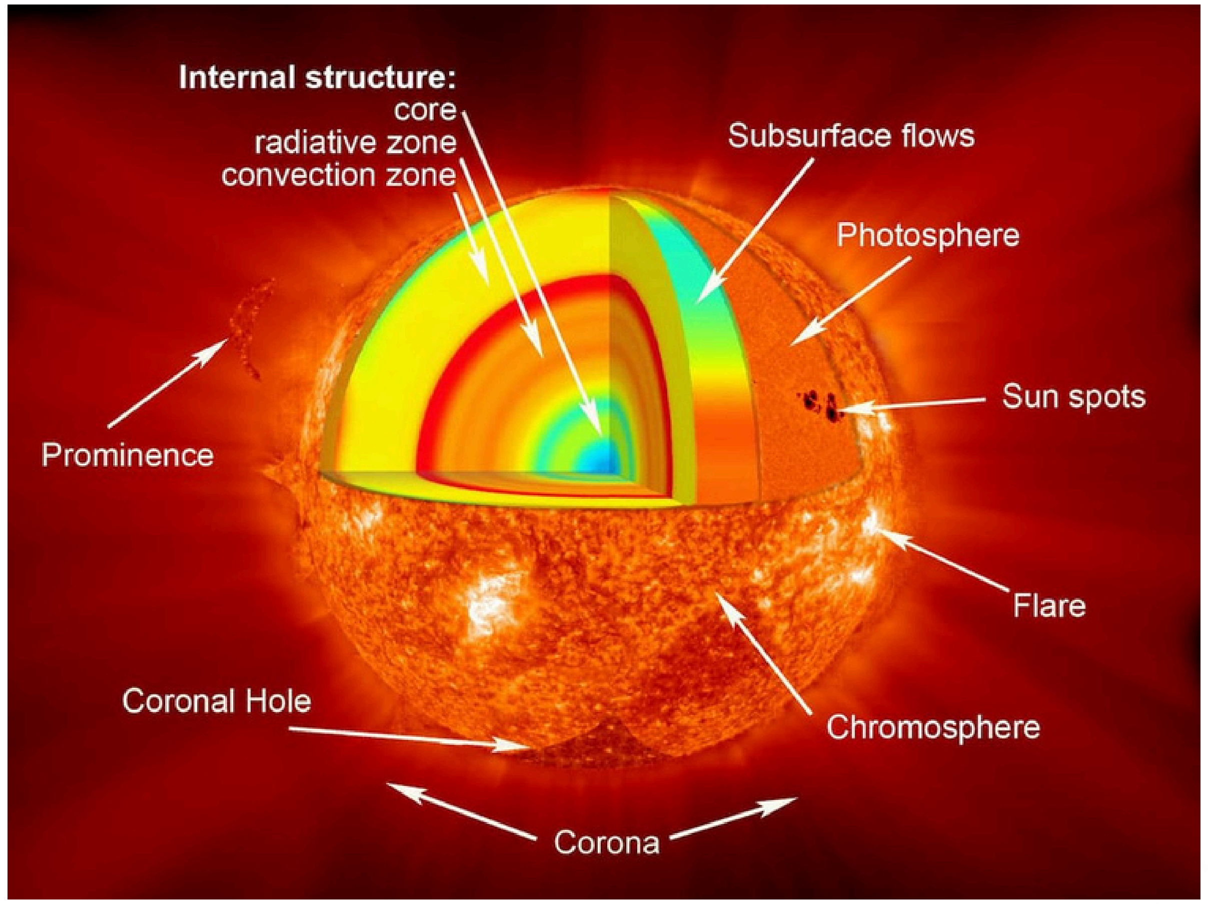
Improving Stellar Models

Assessing the Impact of Updated Opacities and Microdiffusion Using YREC



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Stellar Structure Equations

1. Mass Conservation: $\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \rho}$
(Relates shell radius to enclosed mass and local density)

2. Hydrostatic Equilibrium: $\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4}$
(Balance of gravitational force and pressure gradient)

3. Energy Generation: $\frac{\partial L}{\partial m} = \epsilon$
(Change in luminosity due to local nuclear energy generation rate)

4. Energy Transport : $\frac{dT}{dM} = \frac{-3\,\kappa_R L}{20\,\pi^2 a\,c\,T^3 r^4}$
(Radiative temperature gradient depends on local opacity, pressure, and temperature)

5. Composition Evolution: $\frac{\partial \chi_i}{\partial t} = -\frac{m_i}{\rho}\left(\sum_k r_{ik} - \sum_j r_{ji}\right)$

Tracks mass fraction of isotope due to nuclear reactions.

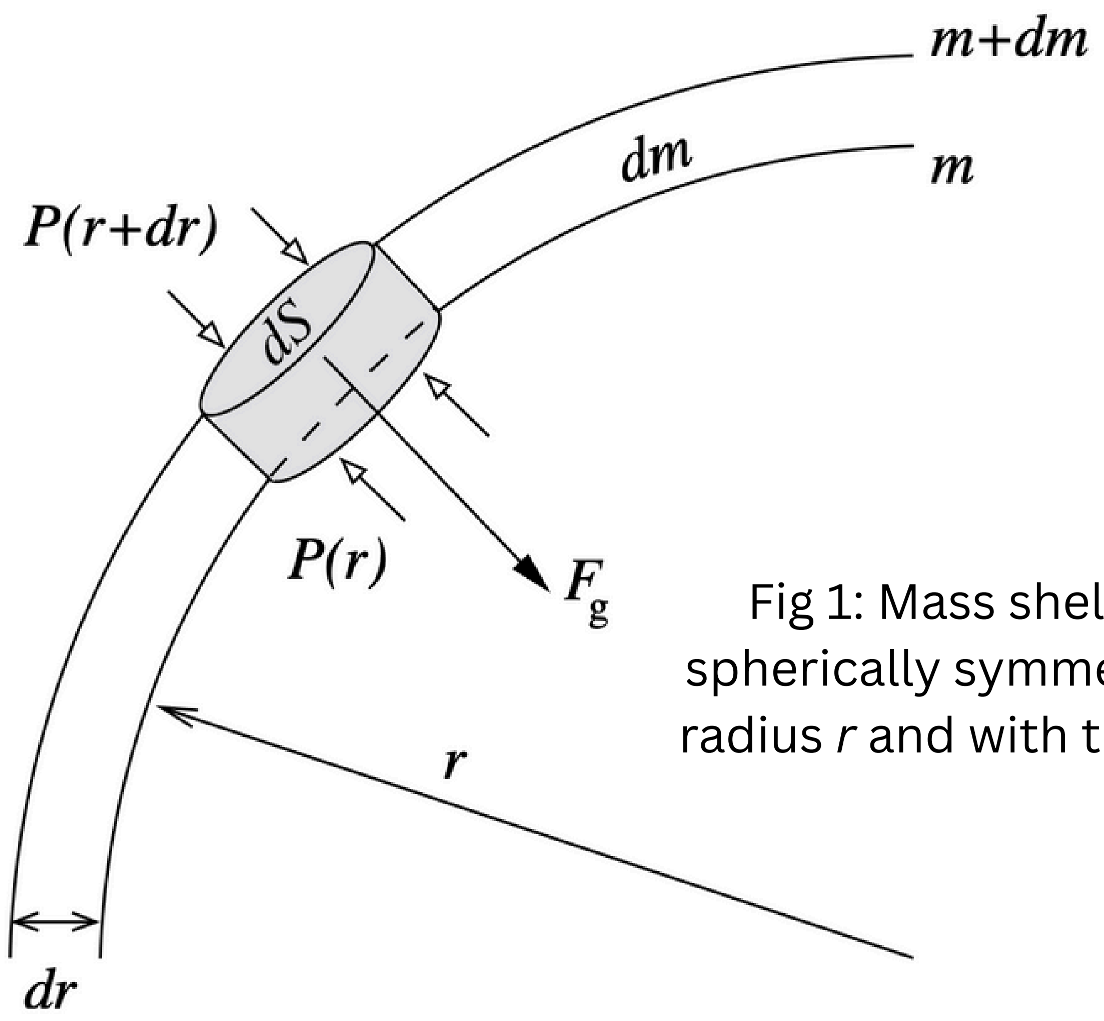

Fig 1: Mass shell inside a spherically symmetric star, at radius *r* and with thickness d*r*.

Numerical solution: Henyey Method

Equations: $$\frac{dy_i}{dm} = f_i(y_1, y_2, y_3, y_4), \quad i = 1 \ldots 4$$

Discretisation over mass shells: $$y_k^{j+1/2} = \frac{1}{2}(y_k^j + y_k^{j+1}), \quad f_i^{j+1/2} = f_i(y_k^{j+1/2})$$

$$A_i^j = \frac{y_i^{j+1} - y_i^j}{\Delta m^j} - f_i^{j+1/2}$$

Boundary Residuals: $$B_1 = y_2^1 - \pi_1(y_1^1, y_4^1), \quad B_2 = y_3^1 - \pi_2(y_1^1, y_4^1)$$

Central Boundary Conditions: $$C_i(y_1^{k-1}, \ldots, y_3^k) = 0, \quad y_1^k = y_2^k = 0$$

$$B_i = 0 \quad (i = 1, 2), \qquad A_i^j = 0 \quad (i = 1, \ldots, 4;\ j = 1, \ldots, k-2), \qquad C_i = 0 \quad (i = 1, \ldots, 4).$$

$$(y_i^j)_2 = (y_i^j)_1 + \delta y_i^j$$

$$B_i^{(1)} + \delta B_i = 0, \quad A_i^{j(1)} + \delta A_i^j = 0, \quad C_i^{(1)} + \delta C_i = 0.$$

$$H \cdot \delta y = -R, \quad \text{with } R = \{B_i, A_i^j, C_i\}$$

YREC: The Yale Rotational Evolution Code

Introduction:

- A 1D stellar evolution code written in FORTRAN.
- Models stars from pre-main-sequence to late evolutionary stages.
- Uses the Henyey relaxation method to solve stellar structure equations.

Key Features:

- Detailed input physics: nuclear networks, EOS, opacity tables.
- Includes mixing-length theory, rotation, and diffusion.
- Adaptive mesh and timestep control.
- Output: internal profiles (P, T, L, ρ, X_i) at each timestep.

Input Physics: Opacity

$$\frac{dT}{dM} = \frac{-3\,\kappa_R\,L}{20\,\pi^2 a\,c\,T^3 r^4}$$

YREC:

- Uses tabulated opacities.
- 4% error in opacity due to interplation errors.
- Does not update relative changes in metal abundances.

YREC_on_fly: $\kappa_R = \kappa(\rho, T, X_i)$

- Real time opacity calculations at each time step and shell
- Opacity is calculated using local temperature, density and composition

Initial Comparison — tabulated vs on-the-fly

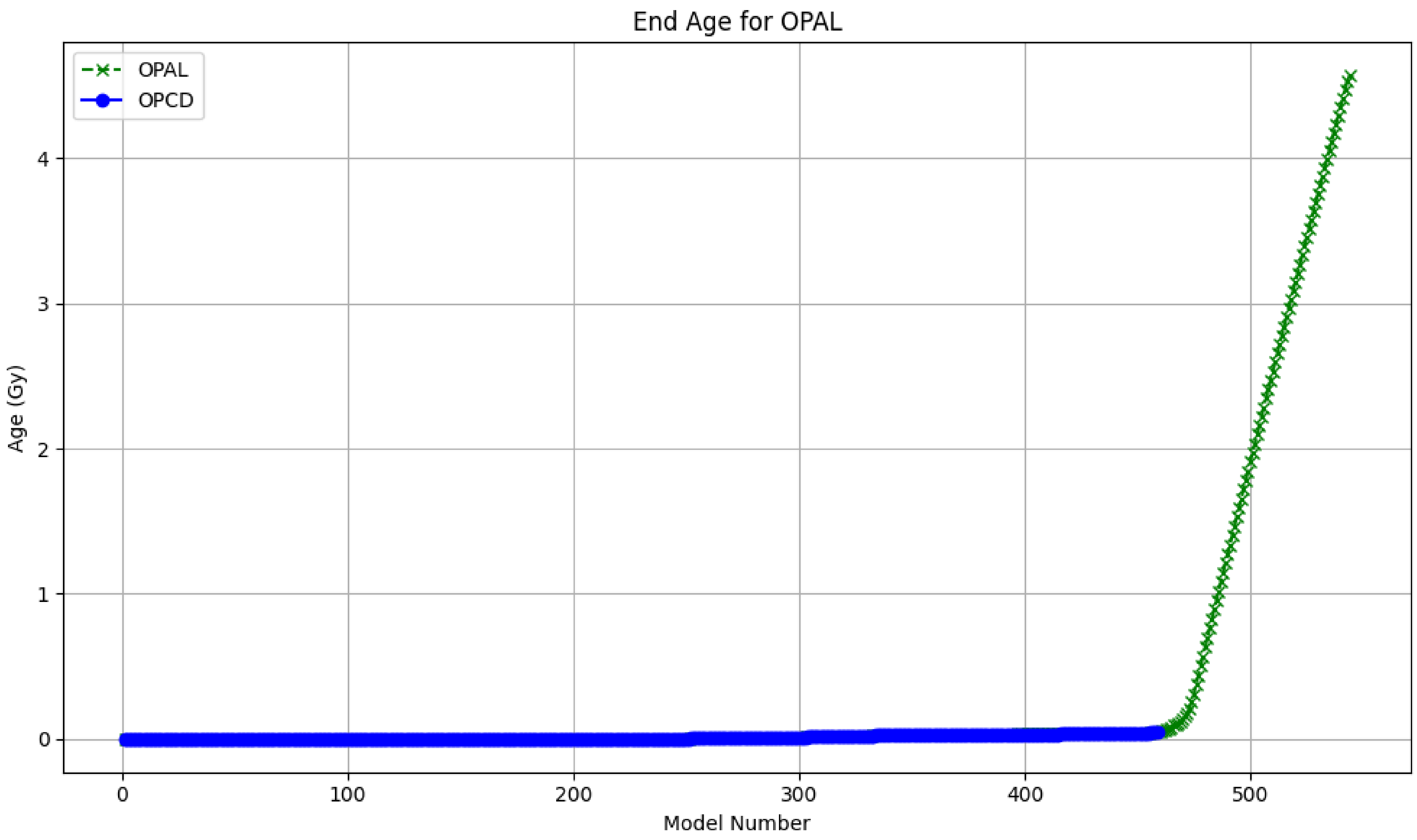

Fig 2: End Age comparison for both runs

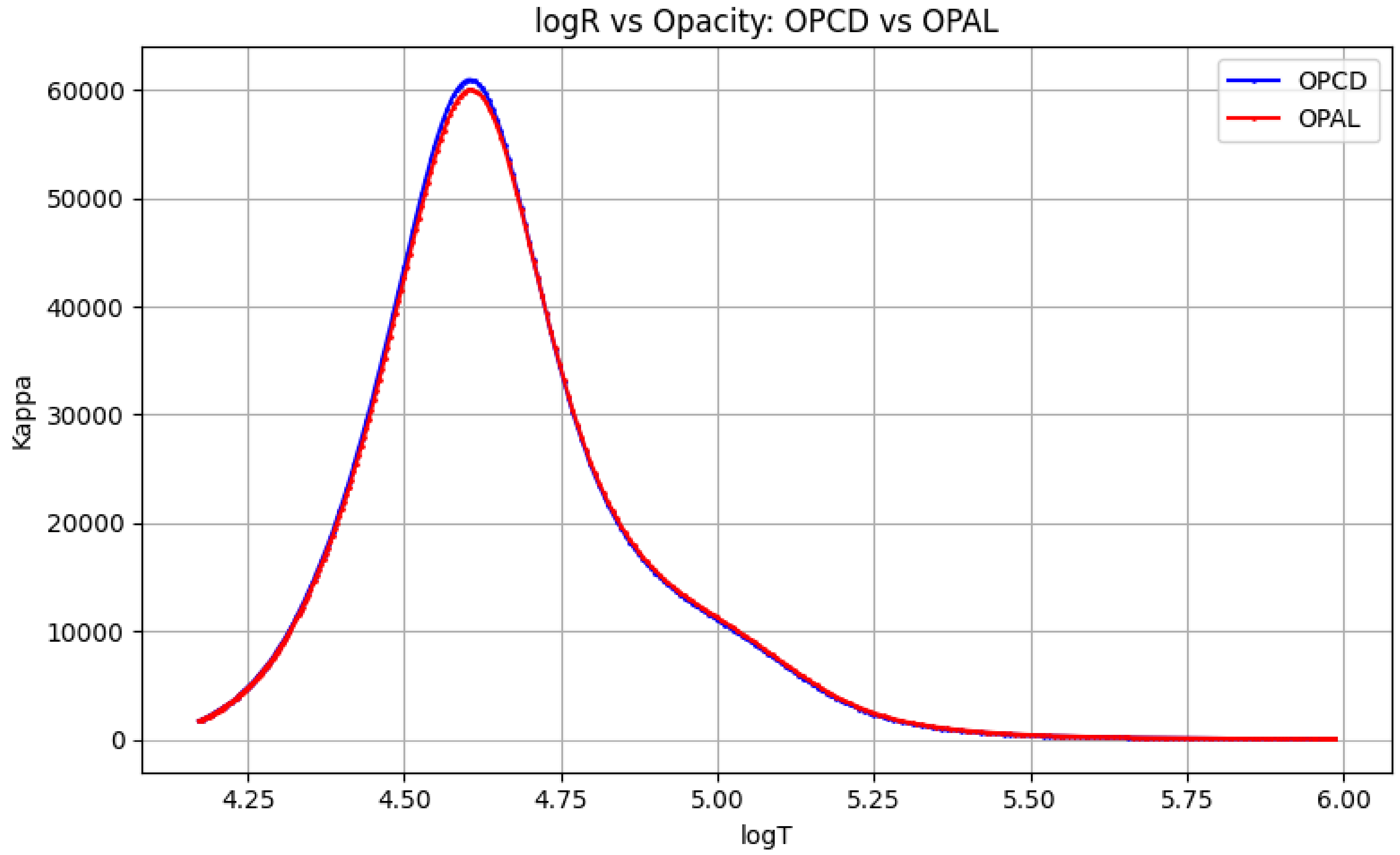

Fig 3: Comparison for 0.05 Gy

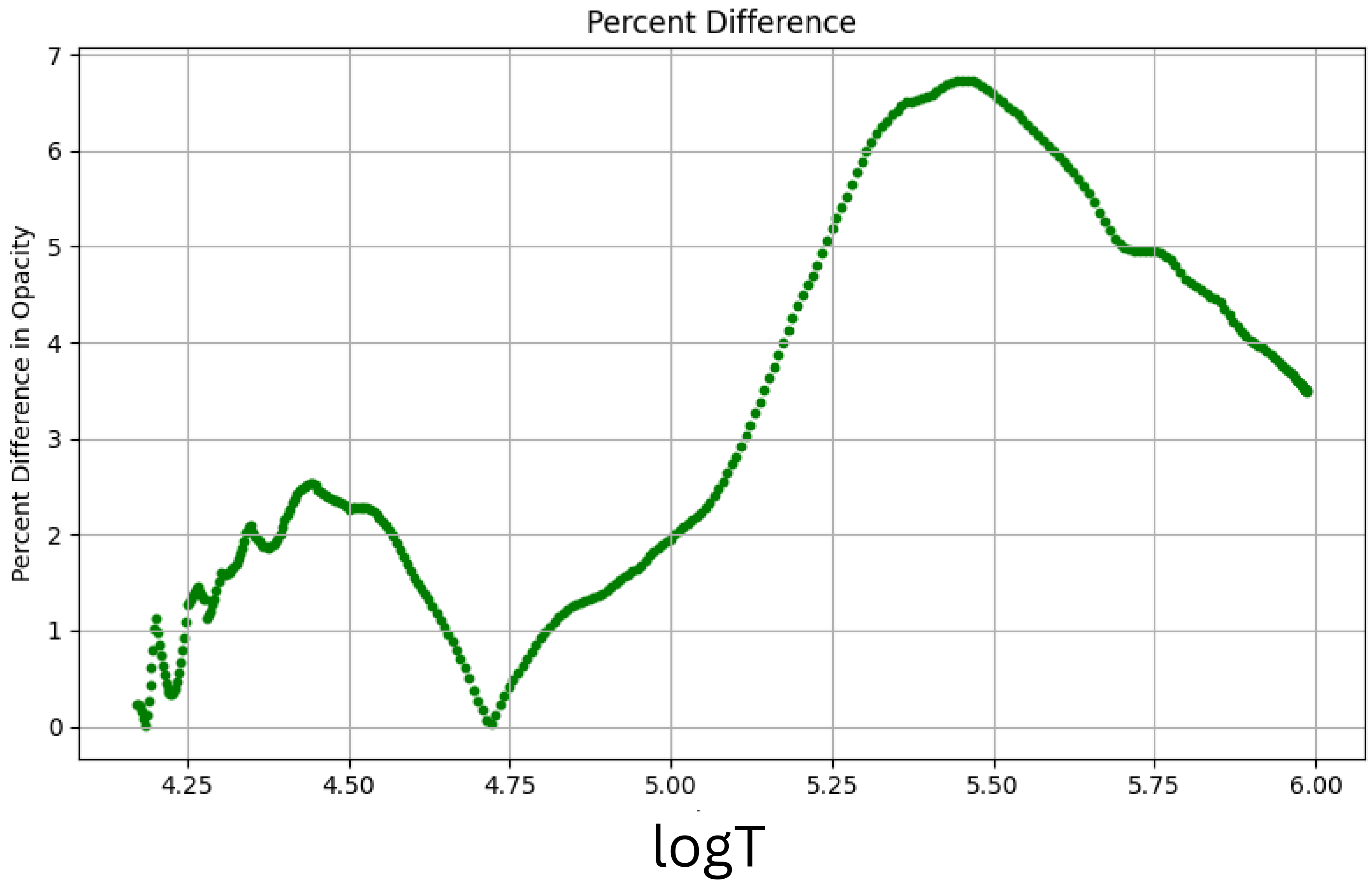

Fig 4: Percentage difference

Radial Profile at 0.05 Gy

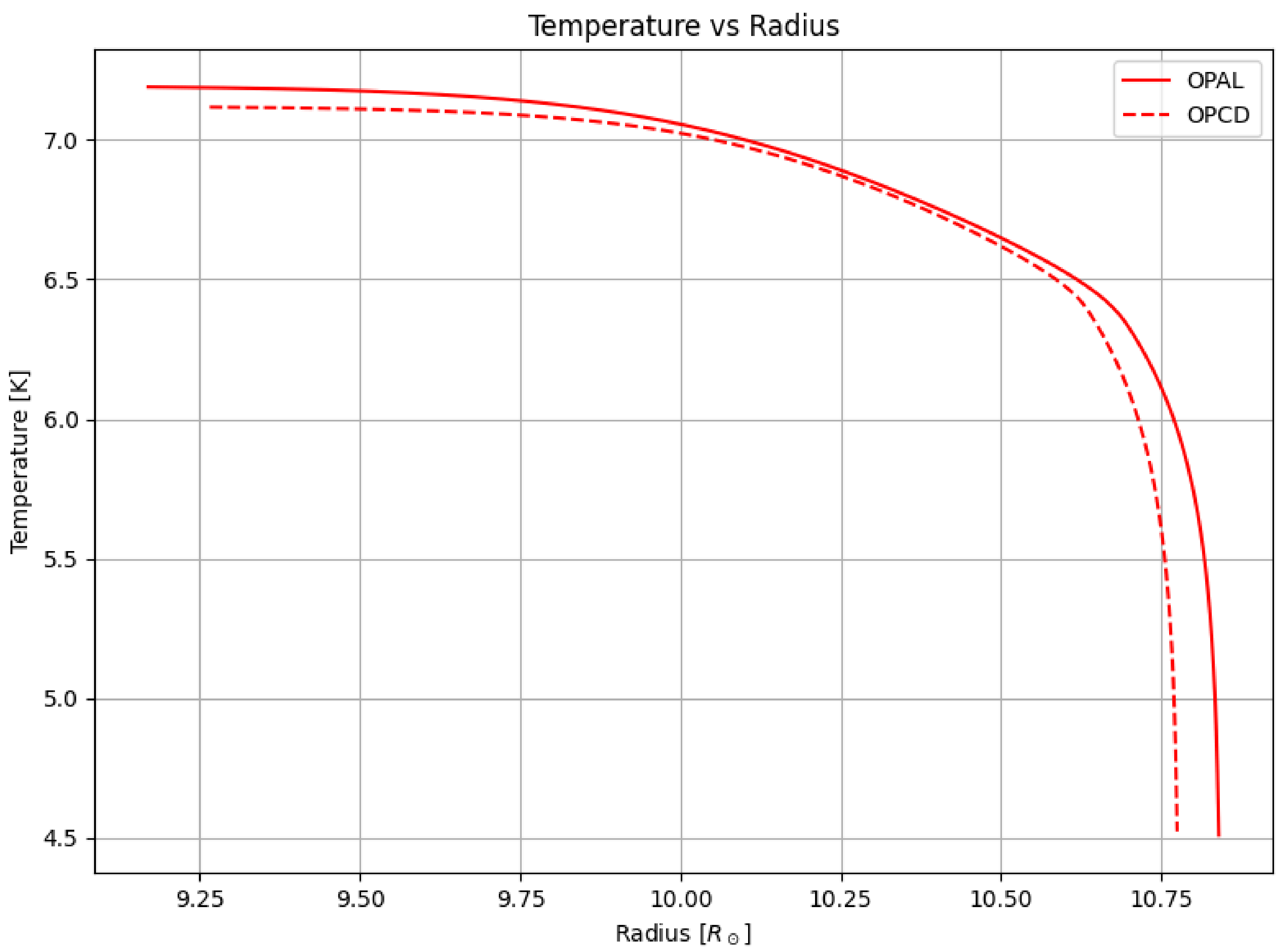

Fig 7: Temp vs Radius

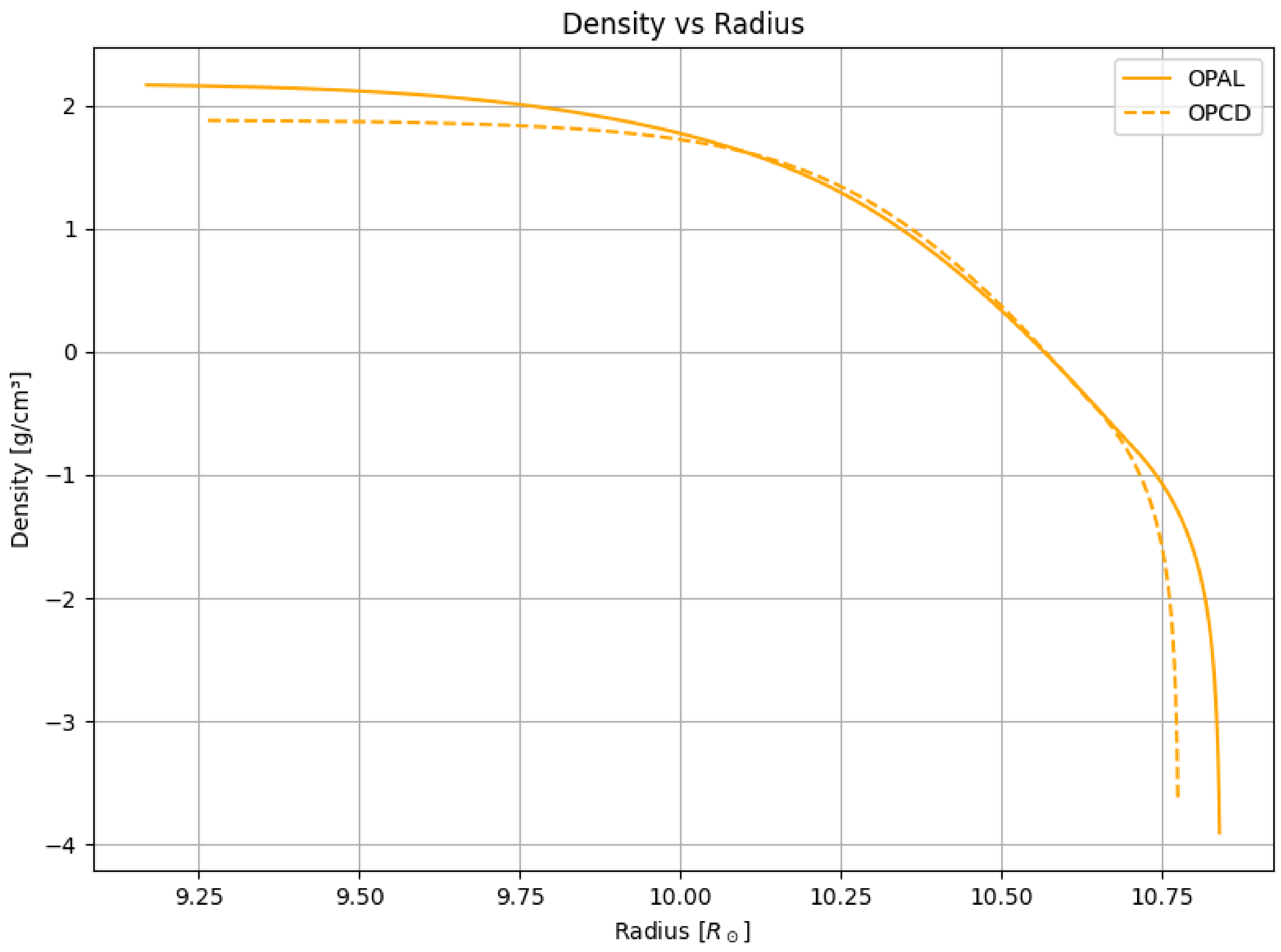

Fig 8: Density vs Radius

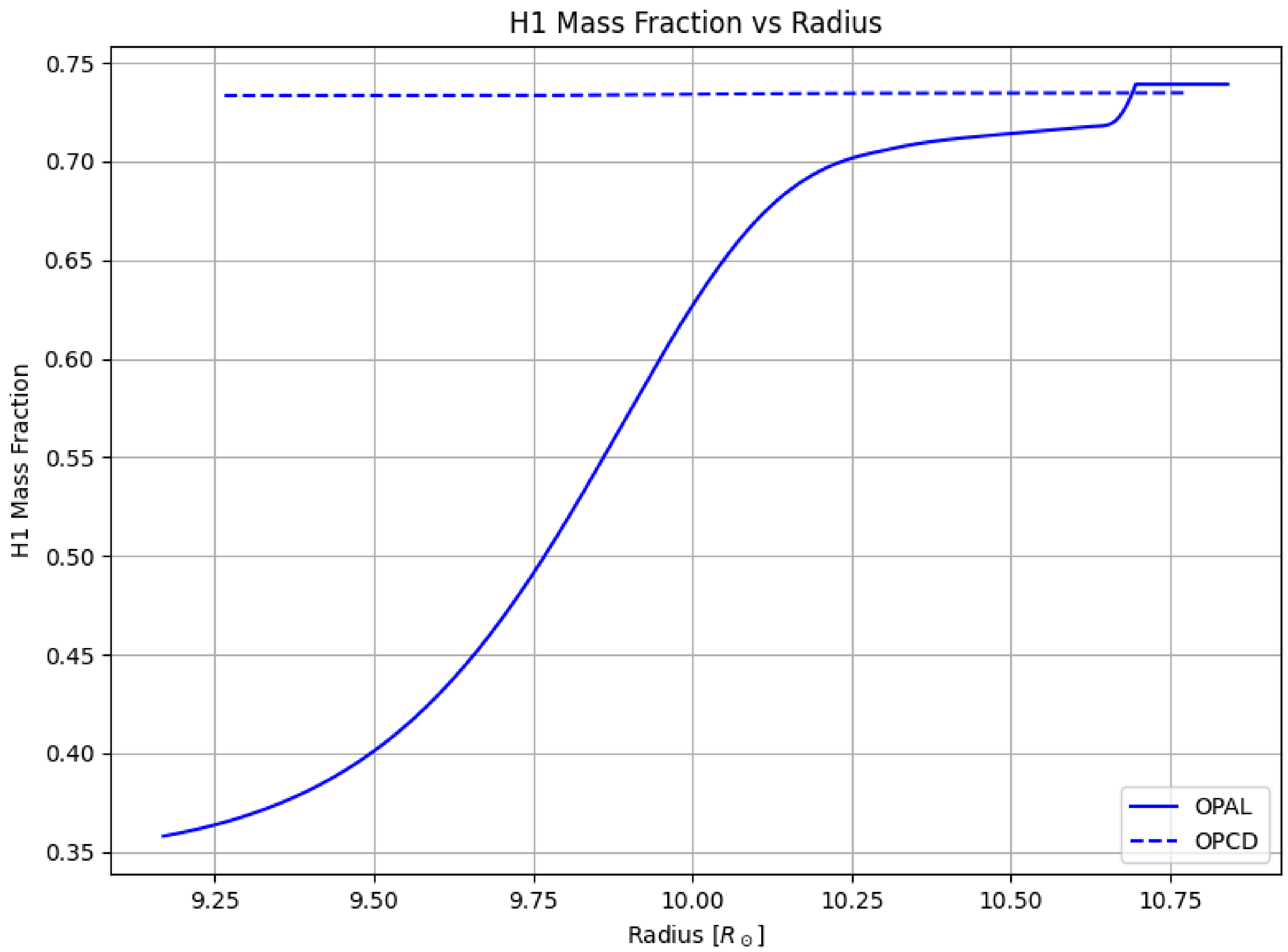

Fig 9: H1 composition vs Radius

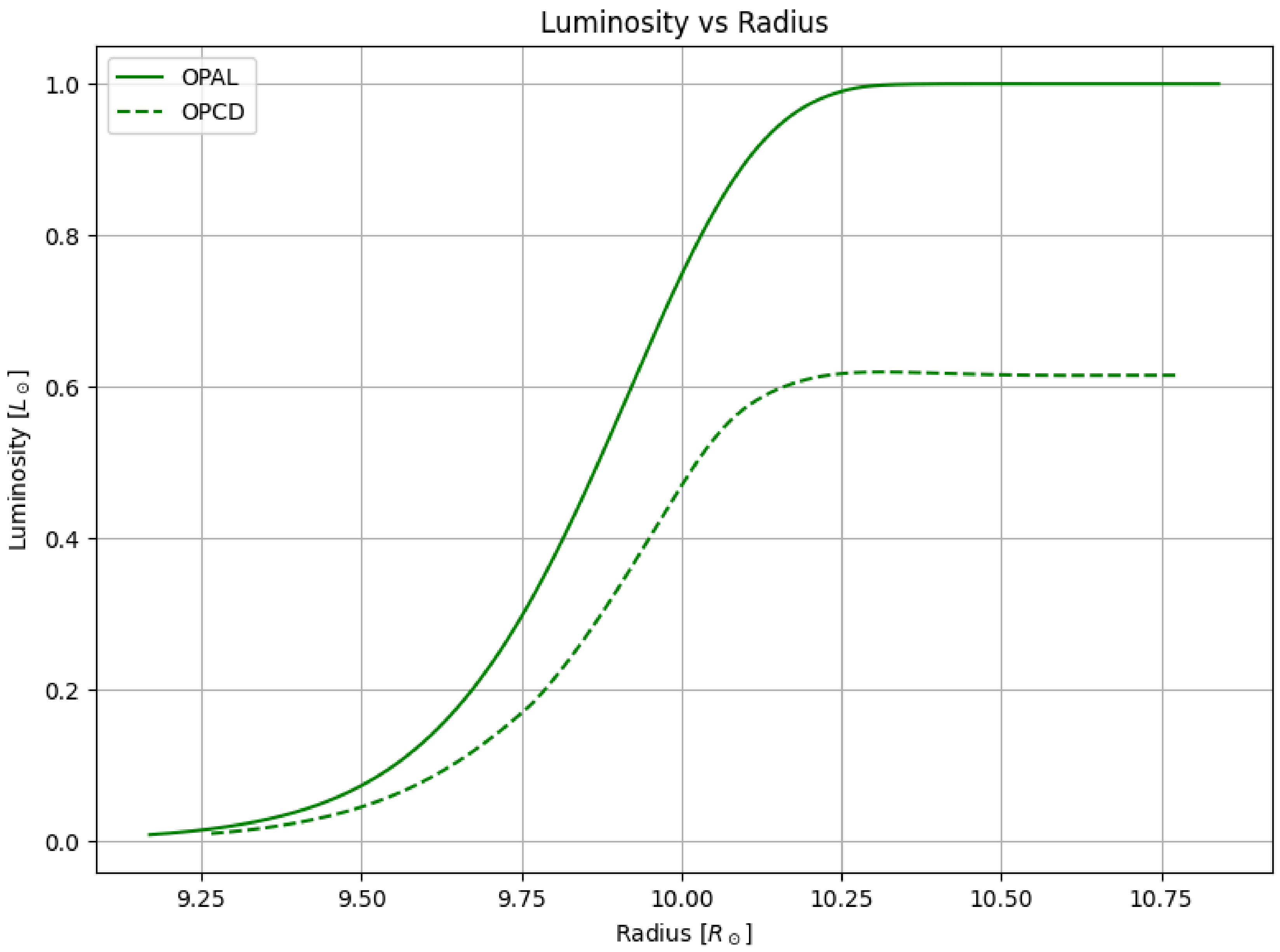

Fig 10: Luminosity vs Radius