

THE INTERIOR STRUCTURE OF THE SOLAR ANALOG BETA CANUM VENATICORUM

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Abstract. We present a detailed interior structure model for the solar analog Beta Canum Venaticorum (β CVn), a key target for astrobiological research, using the MESA (Modules for Experiments in Stellar Astrophysics) stellar evolution code. Our model, calibrated at an age of 8.79 Gyr, accurately reproduces the observed stellar properties with a mass of $0.927M_{\odot}$, radius of $1.110R_{\odot}$, luminosity of $1.330L_{\odot}$, and an effective temperature of 5884 K. The resulting structure features a radiative core where energy is generated primarily via the proton-proton (PP) chain, a radiative zone extending to $0.82R_{\odot}$, and an outer convective envelope. We provide detailed radial profiles for key physical variables, including mass, density, pressure, temperature, energy generation, mass fraction, and temperature gradient. These results provide a self-consistent benchmark for comparative studies of solar-analog stars and a foundational reference for advanced studies of β CVn.

Key words: Stellar Astrophysics – Stellar Structure – Stellar dynamics – Stellar characteristics and properties.

1. INTRODUCTION

Beta Canum Venaticorum (β CVn) is a solar analog star (a star that is photometrically similar to the Sun). Because of its solar-like properties, astrobiologists have listed it as one of the most astrobiologically interesting stars within 10 parsecs of the Sun (Porto de Mello, Fernandez del Peloso, and Ghezzi, 2006; Turnbull, 2015). However, to date, this star has no known planets. Recent radial-velocity analyses show that no Saturn-mass companions are present within ~ 10 au and that the habitable zone could plausibly host several Earth-mass planets in stable, compact configurations, reinforcing β CVn's appeal for direct imaging (Kane *et al.*, 2020). These external dynamical constraints provide helpful context for the interior-structure modeling presented here.

β CVn stars are single stars (Morbey and Griffin, 1987; Reylé *et al.*, 2021). However, it has been described as a spectroscopic binary (Abt and Levy, 1976). The

star β CVn has other names, including Chara, HD 109358, HIP 61317, HR 4785, 2MASS J12334454+4121270, and Gaia DR3 1534011998572555776. This star is located at coordinates $RA=188.43560^\circ$ and $Dec=41.35748^\circ$ with a spectral class of G2/3V (Llorente de Andrés *et al.*, 2021). The star β CVn has a V magnitude of 4.25 ± 0.05 (Van Belle and Von Braun, 2009). According to Gaia DR3 (Vallenari *et al.*, 2023), this star has a parallax of 118.0266 ± 0.1530 mas, corresponding to a distance of 8.473 ± 0.011 parsecs.

The wealth of high-precision observational data for such a nearby and bright star makes β CVn an exceptional candidate for detailed stellar modeling. Accurate stellar parameters are indispensable for defining the boundaries of its habitable zone and for characterizing any exoplanets that may be discovered in the future. Understanding the star’s interior structure and evolutionary state is the first step in comprehensively characterizing it.

To this end, we employ the stellar evolution code, Modules for Experiments in Stellar Astrophysics (MESA). By leveraging available photometric, spectroscopic, and astrometric constraints, we can construct a model of the star’s interior from the core to the photosphere, thereby probing the physical conditions, energy transport mechanisms, and chemical abundance profiles throughout its structure.

In this paper, we present a detailed interior structure model for β CVn. Our primary objective is to derive its fundamental parameters and to explore its internal properties, such as the location of its convection zone base, its central thermodynamic conditions, and the relative contributions of the pp-chain and CNO cycle to its total luminosity. This work aims to provide a holistic model of β CVn to date, serving as a foundational reference for future exoplanet searches and comparative solar-stellar studies.

2. METHODOLOGY

The interior structure and evolution of β CVn were simulated using the open source software suite Modules for Experiments in Stellar Astrophysics (MESA) (Paxton *et al.*, 2011, 2013, 2015, 2018, 2019; Jermyn *et al.*, 2023), version `r23.05.1`. MESA solves the coupled equations of stellar structure and evolution, incorporating a wide range of physical modules. The model was constrained by a critical analysis of fundamental parameters from the literature, compiled in Table 1. The weighted average values for mass, gravity, effective temperature, metallicity, and age were adopted as the target parameters for our model. To ensure robust input parameters for our stellar interior models, we did not rely on a single source in the literature. Instead, we derived the fundamental stellar properties of β CVn by calculating the weighted average of values reported in multiple independent studies. The weighting

Table 1
Fundamental Physical Parameters of β CVn from Literature

Parameter	Value	Reference*	Weighted Average
Mass [$M_{\odot}$]	0.97 ± 0.04	1	0.921 ± 0.015
	$0.98^{+0.02}_{-0.03}$	2	
	0.852 ± 0.023	3	
	1.05 ± 0.14	4	
Radius [$R_{\odot}$]	1.123 ± 0.028	3	1.123 ± 0.028
Surface gravity ($\log g$, cgs)	4.37 ± 0.03	2	4.362 ± 0.026
	4.34 ± 0.05	5	
Effective temperature [K]	6043 ± 183	1	5823 ± 40.58
	5891 ± 51	2	
	5653 ± 72	3	
Luminosity [$L_{\odot}$]	1.151 ± 0.018	3	1.151 ± 0.018
Metallicity [Fe/H]	-0.180 ± 0.020	1	-0.188 ± 0.018
	-0.220 ± 0.04	2	
	-0.30	6	
Age [Gyr]	3.4 ± 3.2	1	8.78 ± 1.21
	$6.80^{+1.37}_{-1.98}$	2	
	14.2 ± 2.1	3	

* References: 1. Llorente de Andrés *et al.* (2021); 2. Aguilera-Gómez, Ramírez, and Chanamé (2018); 3. Boyajian *et al.* (2012); 4. Valenti and Fischer (2005); 5. Wu *et al.* (2011); 6. Holmberg, Nordström, and Andersen (2007).

factors were defined as the inverse square of the reported uncertainties ($w_i = 1/\sigma_i^2$), thereby assigning greater significance to high-precision measurements.

In modeling the interior structure of a star, MESA cannot directly construct a model from the input parameters listed in Table 1. Instead, MESA requires initial conditions corresponding to the star at the Zero-Age Main Sequence (ZAMS), which are then evolved forward to the terminal phases of stellar life. This evolutionary calculation generates a sequence of models at discrete time steps. A model snapshot can then be selected whose age and global properties best match those of the target star for the analysis of its interior structure.

For β CVn, we first estimate suitable initial conditions by comparing its fundamental properties to the grid of evolutionary tracks in Ekström *et al.* (2012). Practically, the star’s measured mass, effective temperature, luminosity, and metallicity were mapped onto the grid, allowing interpolation between tracks to infer an initial mass M_{init} and an initial mass fraction Z_{init} . These values (reported in Table 2) seed a ZAMS model in MESA, which evolves until the track reaches an age at which the model simultaneously reproduces the star’s observed constraints within uncertainties. The age-matched snapshot (8.78 ± 1.21 Gyr) is the one used for all interior-structure diagnostics discussed below.

Table 2

Input Parameters for MESA Modeling

Parameter	Value	Reference
Initial mass [$M_{\odot}$]	0.93	Ekström <i>et al.</i> (2012)
Initial Z	0.01	Calculated from $[\text{Fe}/\text{H}] = \log(Z/Z_{\odot})$ with $Z_{\odot} = 0.0148$ (Salaris and Cassisi, 2005)

3. RESULTS

The MESA simulation produced a model for β CVn at an age of 8.79 Gyr, closely matching its estimated actual age. Table 3 compares the key physical parameters of this model with the established observational values. The model successfully reproduces the mass, radius, surface gravity, effective temperature, and luminosity within the observational uncertainties.

3.1. MASS AND DENSITY PROFILE

In Fig. 1a, the cumulative mass rises steeply with radius, confirming strong central concentration. The mass distribution is heavily concentrated toward its center. Half of the stellar mass is already enclosed by $r \approx 0.236 R_{\odot}$, while 99% of the mass is enclosed by $r \approx 0.845 R_{\odot}$. Consequently, the outer 24% in radius contains only $\sim 1\%$ of the mass, illustrating a very low-mass envelope spread across a large radial extent. This steep central concentration is a consequence of the star's density profile.

The density peaks at the core (Fig. 1b), reaching approximately 380 g/cm^3 . This is over four times the central density of the present Sun (153.86 g/cm^3 , Christensen-Dalsgaard, 2021). The high core density is a result of long-term hydrogen fusion. As lighter hydrogen is converted to heavier helium, the core's mean molecular weight increases, and the core contracts under gravity to maintain pressure support, thus raising the density. From this extremely high central value, density declines sharply with radius. In the outer layers, the density drops by many orders of magnitude, reaching $\sim 10^{-7} \text{ g/cm}^3$ at the surface (similar to the outer atmosphere of the Sun). This steep gradient means the outer envelope contains relatively little mass despite its

Table 3

Comparison of Actual and Modeled Parameters for β CVn

Parameter	Actual Value	Model Value
Mass [$M_{\odot}$]	0.921 ± 0.015	0.927
Radius [$R_{\odot}$]	1.123 ± 0.028	1.110
Surface Gravity ($\log g$, cgs)	4.362 ± 0.026	4.315
Effective Temperature [K]	5823 ± 40.58	5884
Luminosity [$L_{\odot}$]	1.151 ± 0.018	1.330
Age [Gyr]	8.78 ± 1.21	8.79

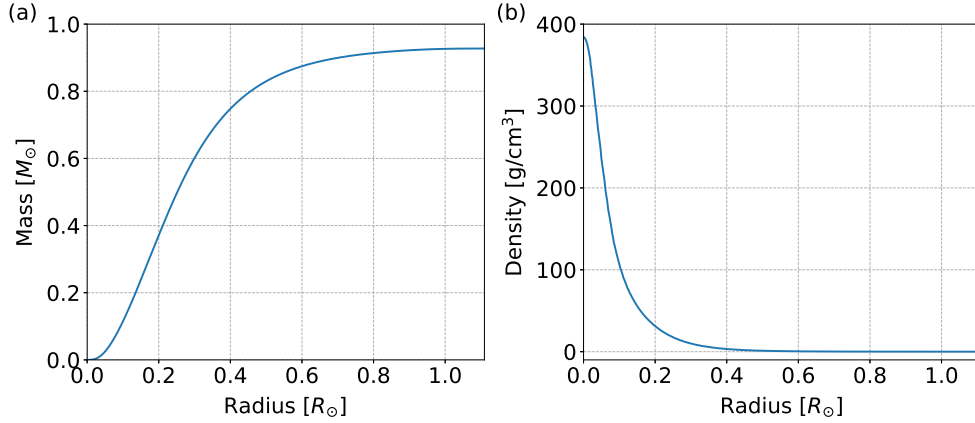


Fig. 1 – The internal structure of β CVn star, plotted as a function of radius for (a) the integrated mass and (b) density (ρ) profile.

volume, whereas the inner regions are very dense and contain most of the mass. The high central concentration of mass also implies a strong central gravitational field, which, in turn, raises the pressure and temperature in the core. In contrast, the outer envelope is extremely diffuse, contributing only a small fraction of the mass despite spanning a large radial extent.

3.2. PRESSURE AND TEMPERATURE PROFILE

The pressure profile $P(r)$ (Fig. 2a) declines by ~ 13 orders of magnitude from center to surface. At the center of β CVn, the pressure reaches on the order of $P_c \approx 5 \times 10^{17} \text{ erg/cm}^3$. This pressure is over twice the central pressure of the Sun ($2.342 \times 10^{17} \text{ erg/cm}^3$ (Bahcall, Pinsonneault, and Basu, 2001)), reflecting the highly compressed, evolved core of β CVn. Pressure decreases sharply with radius, dropping by many orders of magnitude from the core to the surface. In the deep interior (within $0.5 R_{\odot}$), the pressure remains relatively high, but it then falls off rapidly in the outer layers as the overlying mass diminishes. This trend follows from hydrostatic equilibrium: as one moves outward, there is less weight above each layer, resulting in lower pressure needed to support it. Near the surface (photosphere), the gas pressure becomes very low, with only a tiny fraction of its core value, which is consistent with the tenuous nature of the atmospheric layers.

From Fig. 2b, the central temperature is about $T_c \approx 1.85 \times 10^7 \text{ K}$. These extreme conditions are comparable to (slightly hotter than) those in the core of the Sun ($1.57 \times 10^7 \text{ K}$ (Christensen-Dalsgaard, 2021)), and they are sufficient to sustain hydrogen fusion. This elevated core temperature is a consequence of advanced age and partially exhausted core hydrogen of β CVn. Such a temperature is well into the range where proton–proton fusion operates efficiently, and it also starts to activate

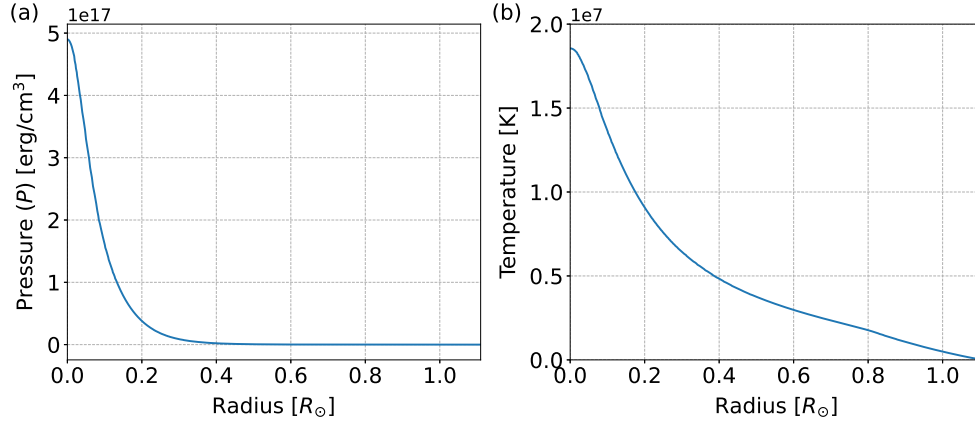


Fig. 2 – The internal structure of β CVn star, plotted as a function of radius for (a) the pressure and (b) temperature (ρ) profile.

the temperature-sensitive CNO cycle. The high pressure is due to the weight of the overlying stellar material, and it is balanced by the outward pressure of the core (from hot gas and radiation).

Both pressure and temperature decrease monotonically with radius, dropping off steeply outside the core. By halfway out (roughly $0.5R_{\odot}$), the temperature has fallen by an order of magnitude from its central value, and at the surface it reaches the effective temperature of about 5880 K (comparable to the effective temperature of the Sun, as β CVn is a G2-3V type star). The pressure in the outer envelope becomes very low (approaching atmospheric pressures near the photosphere). This sharp outward decrease in P and T is expected because, as one moves outward, there is less overlying weight to support, so less pressure is required, and the stellar material can cool due to expansion and radiative losses.

3.3. LUMINOSITY AND ENERGY GENERATION RATE PROFILE

The cumulative luminosity profile $L(r)$ (Fig. 3a) rises from essentially zero at the center to the photospheric value over a very small fraction of the stellar radius, confirming that energy production is highly centralized in β CVn. Quantitatively, the model's surface luminosity is $L \approx 1.33L_{\odot}$. The growth is extremely rapid in the inner core. Half the total luminosity is reached by $r \approx 0.088R_{\odot}$. By $0.23R_{\odot}$, the star has already produced $> 99\%$ of the luminosity. Beyond $\sim 0.3R_{\odot}$, the $L(r)$ curve has essentially saturated, indicating that the envelope contributes negligibly to energy production despite its large radial extent. This means the outer 80% of the star (by radius) transports the energy outward that was produced in the core, without adding to it. The modeled total luminosity of β CVn is about $1.33L_{\odot}$, consistent with its slightly higher effective temperature and larger radius.

The total nuclear energy generation rate (ϵ_{nuc}) and its PP (proton-proton) chain and CNO (carbon, nitrogen, oxygen) cycle components are shown in Fig. 3b. The nuclear energy generation rate per unit mass $\epsilon_{\text{nuc}}(r)$ is sharply peaked toward the center. The profile attains its maximum $\epsilon_{\text{nuc,max}} \approx 17.8 \text{ erg g}^{-1} \text{ s}^{-1}$ at $r \approx 0.02R_{\odot}$, and then declines steeply with radius. The PP chain dominates hydrogen burning across most of the core temperature range. At the same time, the CNO cycle remains a minor contributor, with only approaching a non-negligible fraction very near the center. The CNO cycle can spike above the PP chain energy-generation rate very near the center because of its much steeper T -sensitivity (Kippenhahn, Weigert, and Weiss, 1990).

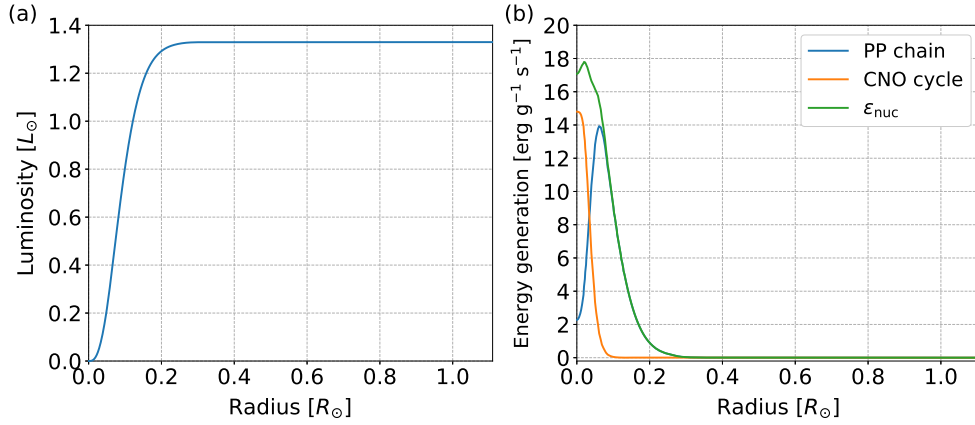


Fig. 3 – The internal structure of β CVn star, plotted as a function of radius for (a) the luminosity and (b) energy generation rate profile.

The peak energy generation rate occurs at the very center, where temperature and density are highest, and it declines rapidly with radius, dropping to negligible levels outside the core. By about $0.3R_{\odot}$, the energy generation rate is effectively zero, and the luminosity of the star is just being carried outward without additional sources. The PP chain is most efficient at the temperatures of $\sim 15 - 18 \times 10^6 \text{ K}$ found in the core. The CNO cycle, which uses carbon, nitrogen, and oxygen as catalysts for hydrogen fusion, is also active in the core of β CVn, but only to a minor degree. Because core temperature slightly exceeds $15 \times 10^6 \text{ K}$, the CNO cycle can proceed, but its energy contribution is much smaller than the energy generation from the PP chain. The energy-generation profile (Fig. 3b) indicates that the PP-chain power far outweighs the CNO power at all radii in the core, confirming PP dominance. Only slight changes in the C, N, and O abundances would indicate that CNO processing is occurring. This proves that β CVn, like the Sun, is a PP-chain dominated main-sequence star, although its slightly hotter core allows a minor CNO assist.

3.4. MASS FRACTION PROFILE

The ^1H and ^4He distributions (Fig. 4a) show a sharp core H depletion and He enrichment. The hydrogen fraction drops steeply, indicating extensive consumption of H into He over the star's lifetime. Correspondingly, the helium mass fraction is significantly elevated in the core. At the center, the mass fraction of $^1\text{H} \approx 0.051$ and $^4\text{He} \approx 0.939$, while in the outermost layers $^1\text{H} \approx 0.73$ and $^4\text{He} \approx 0.26$. Hydrogen rises outward rapidly, with mass fraction of 0.5 by $r \approx 0.109 R_\odot$ and mass fraction of ~ 0.73 approaching the outer layer. Conversely, helium declines from ~ 0.94 at the center to 0.5 near $r \approx 0.105 R_\odot$ and approaches ~ 0.26 in the outer envelope. At a radius of $0.107 R_\odot$, ^1H and ^4He have the same mass fraction of ~ 0.4949 . In the envelope (outside the nuclear-burning core), the composition remains roughly the same as the initial mix because these outer layers have not undergone core nuclear reactions. These gradients map the extent of sustained core H-burning and the degree of central fuel consumption at the current evolutionary stage.

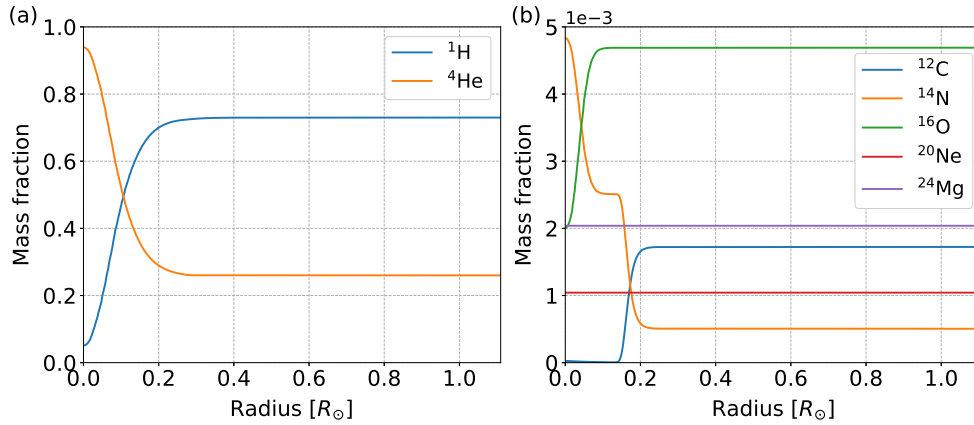


Fig. 4 – Internal structure of β CVn as a function of radius. (a) Mass fractions of H and He, showing core hydrogen depletion. (b) Mass fractions of C, N, O, Ne, and Mg, highlighting abundance changes from the CNO cycle.

From Fig. 4b, subtle but essential shifts are present in the carbon, nitrogen, and oxygen abundance profiles in the core. These shifts are signatures of the CNO cycle at work. In the innermost region, ^{12}C and ^{16}O are slightly depleted, while ^{14}N is enhanced relative to the initial composition. Numerically, at the surface, the mass fractions of ^{12}C , ^{14}N , and ^{16}O are 1.72×10^{-3} , 5.05×10^{-4} , and 4.69×10^{-3} , respectively. At the center, these become around 2.58×10^{-5} , 4.84×10^{-3} , and 2.01×10^{-3} , respectively. This occurs because the CNO cycle, during hydrogen fusion, tends to convert C and O into ^{14}N (via the CN cycle equilibrium). Outside the core ($r > 0.2 R_\odot$), the C, N, O abundances remain at their baseline (initial) levels,

since those elements there have not been transmuted. Other heavier elements like neon (Ne) and magnesium (Mg), which are not involved in H-burning at this stage, show flat profiles where their abundances are essentially unchanged from center to surface (both around 1.04×10^{-3} and 2.04×10^{-3} , respectively, at the center and surface).

3.5. TEMPERATURE GRADIENT PROFILE

The boundary between radiative and convective zones inside β CVn could be determined by comparing the local radiative temperature gradient (∇_{rad}) to the adiabatic gradient (∇_{ad}) using the Schwarzschild criterion. The Fig. 5 shows the profile of those temperature gradient differences. Wherever the radiative gradient exceeds the adiabatic gradient ($\nabla_{\text{rad}} > \nabla_{\text{ad}}$), the energy transport by radiation is insufficient and the layer becomes convectively unstable (leading to convection). Conversely, if $\nabla_{\text{rad}} < \nabla_{\text{ad}}$, the structure is stable and energy is carried by radiation.

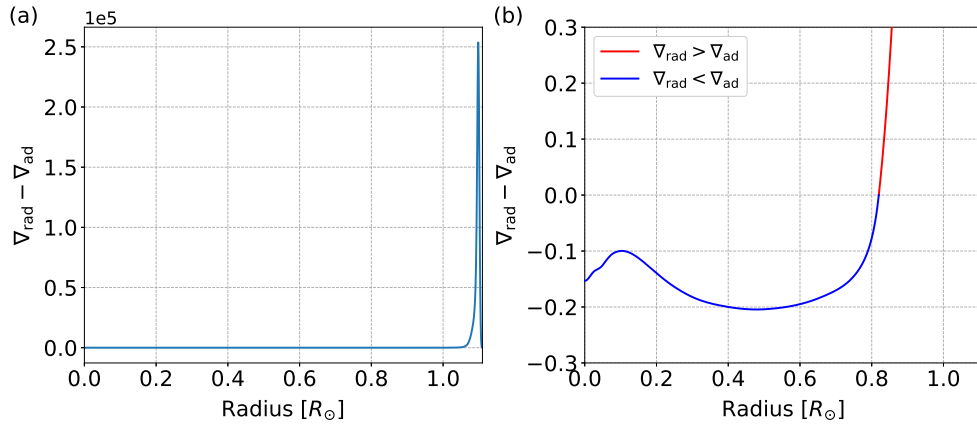


Fig. 5 – (a) The difference between the radiative (∇_{rad}) and adiabatic (∇_{ad}) temperature gradients. (b) A zoomed-in plot of panel (a).

Throughout most of the interior, $\nabla_{\text{rad}} - \nabla_{\text{ad}} < 0$, indicating convective stability and radiative energy transport. Approaching the outer envelope, $\nabla_{\text{rad}} - \nabla_{\text{ad}}$ rises and crosses zero, the start of convective instability. At $\nabla_{\text{rad}} - \nabla_{\text{ad}} = 0$ gives the base of the convective envelope at radius of $r \approx 0.82 R_{\odot}$. The mass enclosed from the center to this radius is $\sim 0.916 M_{\odot}$ (98.8% of the total mass). The convective envelope contains only $\sim 1.2\%$ of the stellar mass despite spanning $\sim 26\%$ of the radius. This implies β CVn has a large radiative interior containing most of its mass, with a shallow convective layer that develops only near the surface.

Based on the profiles above, three primary zones in the interior of β CVn and their boundaries can be identified, as illustrated in Fig. 6.

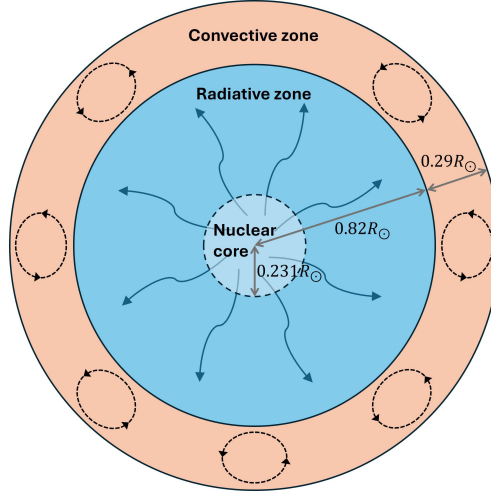


Fig. 6 – Diagram of the energy transport zone in the interior of β CVn.

- **Nuclear-burning core:** Inner $\sim 0.231R_{\odot}$ ($\sim 20.8\%$ of the radius). This central zone is where 99% of the stellar luminosity is produced. The core is radiative (no convective core present), as ∇_{rad} remains below ∇_{ad} in this low-mass star's center. All energy is produced in a radiative core and radiates outward. Physically, this corresponds to the helium-enriched, high-temperature region sustaining proton-proton chain reactions. Beyond this, the energy generation rate is effectively zero and the composition transitions back to mostly hydrogen.
- **Radiative zone:** The radiative zone is defined by the manner in which energy is transported. Therefore, the nuclear-burning core is also included in the radiative zone. In this zone, energy is transported by radiative diffusion rather than convection. The radiative temperature gradient is shallower than the adiabatic gradient, so the stratification is stable against convection. This radiative zone encompasses most of the volume and mass of β CVn. The temperature falls from 18.6×10^6 K at the center, then to 8.1×10^6 K at the core boundary, and down to 1.6×10^6 K at the radiative-convective zone boundary. Surrounding the core (from $0.231R_{\odot}$ to $0.82R_{\odot}$) is a large radiative interior that extends through most of the radius of β CVn.
- **Convective zone:** This is a thin convective layer occupying the outer $\sim 26\%$ of the stellar radius. The convective zone starts at approximately $0.82R_{\odot}$ and extends to the surface. Here, the radiative gradient becomes steeper than the adiabatic gradient. As a result, energy in this outer envelope is transported by convective motions rather than by radiation alone. Despite its significant radial extent, this convective envelope contains only a small fraction of the total mass.

This outer convection zone is what drives surface phenomena, such as granulation. The convective envelope of β CVn is slightly thinner compared to the convective envelope of the Sun, which extends from $\sim 0.71R_{\odot}$ to the surface (Christensen-Dalsgaard, Gough, and Thompson, 1991).

4. CONCLUSIONS

In this study, we aimed to construct a detailed interior model of the solar analog β CVn to characterize its fundamental properties and internal structure better. Our MESA model yields a coherent picture of β CVn as a main-sequence G-dwarf. We derive fundamental parameters of $M_{\star} \approx 0.927M_{\odot}$, $R_{\star} \approx 1.1097R_{\odot}$, and $L_{\star} \approx 1.33L_{\odot}$. The model is characterized by a strong central concentration ($T_c \approx 1.86 \times 10^7$ K, $\rho_c \approx 3.84 \times 10^2$ g/cm³) and a large radiative zone extending to $0.82R_{\odot}$, which is topped by a thin convective envelope. Energy production is confined to the deep interior and is dominated by the PP-chain, consistent with a star of this mass. The resulting abundance profiles confirm ongoing core hydrogen burning and a chemically quiescent envelope, with CNO-processed material remaining confined to the core.

The detailed structure derived here provides essential context for understanding stellar evolution near one solar mass. Relative to the Sun, our model of β CVn presents a slightly shallower convective envelope and a modestly hotter core, which is consistent with its higher luminosity at a near-solar mass. These findings are broadly consistent with the physical parameters reported in the literature, but provide a much-needed physical model of its interior, which was previously lacking. The confirmation of a purely radiative core reinforces theoretical predictions for stars just below the solar mass. It highlights β CVn as a crucial benchmark for calibrating models of G-type dwarfs. The lack of dredge-up of CNO-processed material supports the standard assumption that surface abundances in such stars remain representative of their initial composition.

The model results depend directly on the adopted input physics and the assumed initial parameters, particularly stellar mass and metallicity. While our final parameters are consistent with observational constraints, they could be further refined to improve accuracy. Future asteroseismic observations, potentially from ground-based networks or future space missions, would be invaluable for probing the core structure and precisely determining the extent of the convective envelope, thereby testing the predictions of this model. Furthermore, a more detailed spectroscopic analysis could provide tighter constraints on the initial chemical composition, enabling a more robust calibration of its evolutionary state.

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