Long-Term Evolution of the Habitable Zone around HD 20794: Implications for Planetary Habitability

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Introduction

HD 20794 — A Metal-Poor Solar Analogue

Stellar Parameters [1]

Parameter	Value
Spectral type	G6 V
V mag	4.34
Distance	6.04 pc
$T_{\rm eff}$	5368 ± 64 K
$\log g$	4.39 ± 0.03
[Fe/H]	-0.42 ± 0.02
$M/M_\odot$	≈ 0.79
$R/R_\odot$	0.93 ± 0.03
Age	8–10 Gyr

Why HD 20794?

- Nearby ($\sim$6 pc), bright, well-studied [1]
- Metal-poor: $[\mathrm{Fe/H}] \approx -0.42$ [1,6]
- Old thick-disc/Population II kinematics [5,7]
- Hosts a compact **multi-planet system** [1]
- Low stellar activity $\Rightarrow$ clean RV signal
- Valuable benchmark for **low-metallicity stellar evolution** [8,9]

The Planetary System of HD 20794

Three Confirmed Planets [1]

Planet	Period (d)	m ($M_\oplus$)	a (AU)
b	18.3	2.15	0.12
c	89.7	2.98	0.36
d	**647.6**	**5.82**	**≈1.35**

HD 20794 d

- Super-Earth candidate with $m = 5.82\ M_\oplus$
- Semi-major axis ∼**1.3541 AU** — near the habitable
- zone Described as *"likely a rocky planet in the HZ"* [1]
- High-priority target for atmospheric characterisation

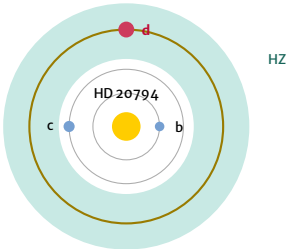


Figure 1: Schematic of the HD 20794 system. Planet d **(red)** sits inside the habitable zone **(green shading).**

Key Question

How long has **Planet d** actually been inside a habitable zone, & will it remain there?

Modelling HD 20794 with MESA

Grid-Based Stellar Evolution with MESA

Grid Design — 252 Models

Parameter	Range
Mass $M/M_\odot$	0.78 – 0.80
$\alpha_{\rm MLT}$	1.2 – 1.8
Mesh coefficient	0.1 – 2.0
Metallicity Z	0.0045 – 0.0050
Boundary conditions	photosphere / τ_{100}

Nuclear Network

Extended `pp_cno_extras_o18_ne22_pcl.net` including the Phosphorus–Chlorine (PCl) cycle for odd-Z nuclei ($A = 31 - 35$).

Modelling Setup

- Pre-main-sequence initialisation (`create_pre_ms = .true.`)
- Evolved to stopping condition: $t = 10$ Gyr
- Energy equation in differential form (`dedt`)
- Gold tolerances for tight Newton convergence
- Adaptive timestep and mesh refinement
- History recorded every timestep

Selection Criterion

χ^2 minimisation against $T_{\rm eff}$, $\log g$, L, R, age. Models with $1 \leq \chi^2_{red} \leq 2$ accepted.

The Phosphorus–Chlorine (PCl) Cycle

Motivation

- Standard networks stop at the CNO cycle
- HD 20794 has measured ^{31}P and ^{35}Cl abundances
- We extend to the $A = 31 - 35$ odd-Z mass range
- Isotopes added: ^{31}P, ^{32}S, ^{33,34,35}Cl, ^{34,35}Ar

PCl Cycle Reactions [10]

$$^{31}\mathrm{P}(p,\gamma)^{32}\mathrm{S}(p,\gamma)^{33}\mathrm{Cl}(p,\gamma)^{34}\mathrm{Ar}(\beta^{+}\nu_e)^{34}\mathrm{Cl}(\beta^{+}\nu_e)$$
$$^{34}\mathrm{S}(p,\gamma)^{35}\mathrm{Cl}(p,\alpha)^{32}\mathrm{S}$$

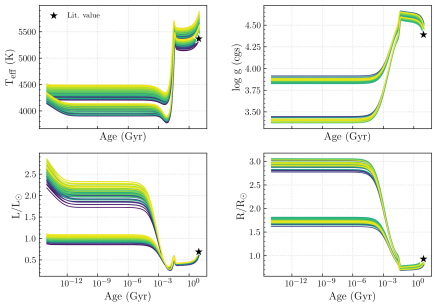


Figure 2: Evolutionary Tracks of HD 20794 Models: Effective Temperature, Surface Gravity, Luminosity, and Radius vs. Age

Results & Calibration

Best-Fit Stellar Model

Best-Fit Parameters

Parameter	Model	Observed
$M/M_\odot$	0.80	0.79 ± 0.02
Age (Gyr)	≈ 9	8–10
$T_{\rm eff}$ (K)	5365	5368 ± 64
$\log g$	4.40	4.39 ± 0.03
$L/L_\odot$	0.690	0.687 ± 0.003
$R/R_\odot$	0.932	0.93 ± 0.03
$\alpha_{\rm MLT}$	1.4–1.6	—
Z	0.0050	—

Selection from 252 Models

- χ^2 minimised against five observables
- $1 \leq \chi^2_{red} \leq 1$ criterion applied
- Best model: $M = 0.80\,M_\odot$, age ≈ 9 Gyr
- $\alpha_{MLT} = 1.4 - 1.6$, τ_{100} atmosphere

Conclusion

All observed stellar parameters are reproduced **within their uncertainties.** Standard stellar evolution theory applies to this metal-poor G dwarf.

Surface Abundance

Surface Abundances $\varepsilon(X)$

Species	Model	Observed	Ref.
^{31}P	≈ 5.01	~ 5.07	[6]
^{32}S	≈ 6.65	~ 6.65	[6]
^{35}Cl	≈ 4.73	~ 4.73	[6]

Interpretation

- Abundances **consistent with natal chemistry**
- No measurable depletion over $\sim$9 Gyr
- Enrichment from core-collapse supernovae preserved throughout evolution

Conclusion

The final selection yielded a best-fit model at $M = 0.80\,M_{\odot}$, Age $\sim$9 Gyr, $\alpha_{\mathrm{MLT}} = 1.4$–$1.6$, mesh resolution $= 1.0$–2.0, and $Z = 0.0050$.

Publication

This work has been published in *MNRAS* as: M. Medhi, M. Deka, K. Saha, V. B. Thapa, and U. Mahanta, "A theoretical study of the structure and elemental abundances of HD 20794," *Mon. Not. R. Astron. Soc.* **548**, stag802 (2026), doi:10.1093/mnras/stag802 [2].

Habitable Zone Evolution of HD 20794

Habitable Zone Framework

Conservative HZ [3,4]

- **Inner edge**: Runaway Greenhouse limit — stellar flux drives irreversible water loss
- **Outer edge**: Maximum Greenhouse limit — CO_2 clouds can no longer warm the surface
- Most physically robust estimate

Optimistic HZ

- **Inner**: Recent Venus criterion ($\sim$1 Gyr ago)
- **Outer**: Early Mars criterion ($\sim$3.8 Gyr ago)
- Extends both edges based on Solar System evidence

HZ Migration

As a main-sequence star ages:

$$L_\star \uparrow \Rightarrow \text{ HZ boundaries shift outward}$$

We couple the **Kopparapu et al. 2013, 2014 prescriptions** to our MESA best-fit model ($M = 0.80\,M_\odot$, age ≈ 9 Gyr) to compute the **time-dependent HZ** of HD 20794 [3,4].

Key Question

Does HD 20794 d ($a \approx 1.35$ AU) remain in-side the habitable zone across the **full main-sequence lifetime**?

HZ Evolution: The Main Result

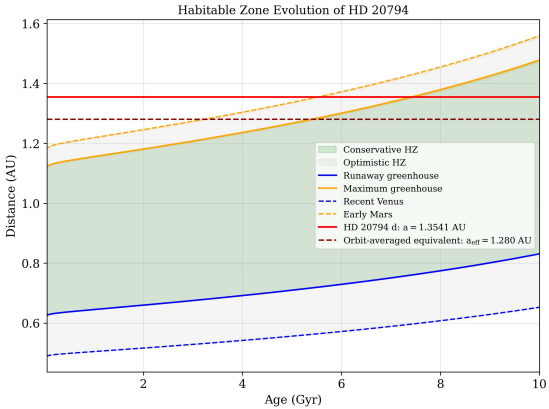


Figure 3: Habitable zone boundaries of HD 20794 d as a function of stellar age. The blue dashed line marks the orbit of HD 20794 d at ∼1.35 AU.

Conservative HZ Boundaries

Age (Gyr)	Inner (AU)	Outer (AU)
0.05	0.63	1.12
5	0.74	1.31
10	0.83	1.48

4.61 / 6.79 Gyr

Estimated HZ residence time

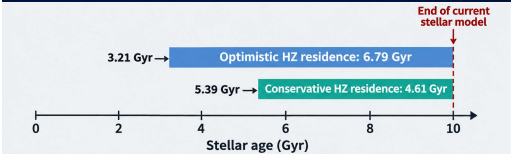
Based on orbit-averaged stellar irradiation, HD 20794 d enters the conservative HZ at approximately 5.39 Gyr and the optimistic HZ at 3.21 Gyr. The planet remains within both HZ limits at the end of the 10 Gyr stellar evolution track.

Significance for Planetary Habitability

What This Means

- **HD 20794 d enters the habitable zone during stellar evolution**, with entry at approximately 3.21 Gyr (optimistic) and 5.39 Gyr (conservative).
- **Extended HZ residence:** approximately 6.79 Gyr (optimistic) and 4.61 Gyr (conservative) within the current 10 Gyr model.
- The low metallicity of HD 20794 provides an interesting case for studying potential planetary habitability around metal-poor stars.
- Demonstrates how calibrated MESA stellar models can be coupled with habitable-zone calculations to investigate the long-term evolution of planetary environments.

Context: Long-Lived HZ Planets



HD 20794 d remains within both HZ limits at 10 Gyr; the calculated residence times are lower limits.

Based on orbit-averaged irradiation: a = 1.3541 AU, e = 0.45, a_{eff} = 1.280 AU.

Conclusions

Summary & Conclusions

Stellar Modelling (MESA)

1. Grid of **252 models** — $M = 0.78$–$0.80\,M_\odot$, varying $\alpha_{\rm MLT}$, mesh, Z, atmosphere
2. Best-fit: $M = 0.80\,M_\odot$, age ≈ 9 Gyr
3. All observed parameters reproduced **within uncertainties**
4. Predicted PCl abundances match spectroscopy: $\varepsilon(^{31}P) \approx 5.01$, $\varepsilon(^{32}S) \approx 6.65$, $\varepsilon(^{35}Cl) \approx 4.73$
5. Natal chemical signatures **preserved** over Gyr timescales

Habitable Zone

1. Conservative HZ migrates outward: inner edge shifts from 0.63 to 0.83 AU, while the outer edge moves from 1.12 to 1.48 AU over 0.05-10 Gyr.
2. HD 20794 d (a=1.354 AU) enters the optimistic and conservative HZ at approximately 3.21 and 5.39 Gyr, respectively, based on orbit-averaged irradiation.
3. **Estimated HZ residence:** approximately 6.79 Gyr (optimistic) and 4.61 Gyr (conservative), within the current 10 Gyr model.
4. Demonstrates how **calibrated MESA stellar models** can be coupled with HZ calculations to investigate the long-term evolution of planetary environments.

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Appendix: Observational Constraints

Table 1: Observed parameters of HD 20794 used for model calibration

Parameter	Value	Uncertainty	Reference
Spectral type	G6 V	—	Nari et al. (2025)
V (mag)	4.34	—	Gaia DR3 (2022)
Distance (pc)	6.00 ± 0.01	± 0.01	Gaia DR3 (2022)
$T_{\rm eff}$ (K)	5368	± 64	Nari et al. (2025)
$\log g$ (dex)	4.39	± 0.03	Nari et al. (2025)
$L/L_\odot$	0.6869	± 0.0026	Nari et al. (2025)
$R/R_\odot$	0.93	± 0.03	Nari et al. (2025)
$M/M_\odot$	0.79	± 0.02	Cretignier et al. (2021)
[Fe/H] (dex)	-0.42	± 0.02	Nari et al. (2025)
Age (Gyr)	8–10	—	Casagrande et al. (2011)
$\varepsilon(^{31}\mathrm{P})$	~ 5.07	—	Maas et al. (2017)
$\varepsilon(^{32}\mathrm{S})$	~ 6.65	—	Maas et al. (2017)
$\varepsilon(^{35}\mathrm{Cl})$	~ 4.73	—	Maas et al. (2017)

Thank You

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