Characterising the Potential for Planetary Habitability: A Study of the Temporal Evolution of Exoplanet Habitable Zones

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Introduction

As the Earth is our only example of a planet-star system harbouring life, we can extrapolate from this to identify analogue exoplanet systems where the conditions for life to exist may also arise to be considered 'habitable'.

To explore habitability both as a concept and applied to exoplanetary systems, it is useful to model Habitable Zone (HZ) evolution throughout the stellar lifetime [1,2], in order to define the limits of evolving habitable zones to better characterise habitability status of planets.

HZ modelling is a tool to allow us to make predictions about *if* or *when* these planets modelled are potentially habitable now, may have previously been or could be in the future. The potential for life detection increases with extended time spent in a temporal HZ spanning multiple stellar evolutionary periods [3], overlooked by many existing HZ studies but forming the focus for this project.

Objectives

- Exploring temporal HZ evolution effect on habitability status of planets
- Generalising HZ evolution dependence on stellar/planetary parameters
- Using hypothetical star-planet systems to investigate albedo and stellar metallicity relationship to HZ evolution

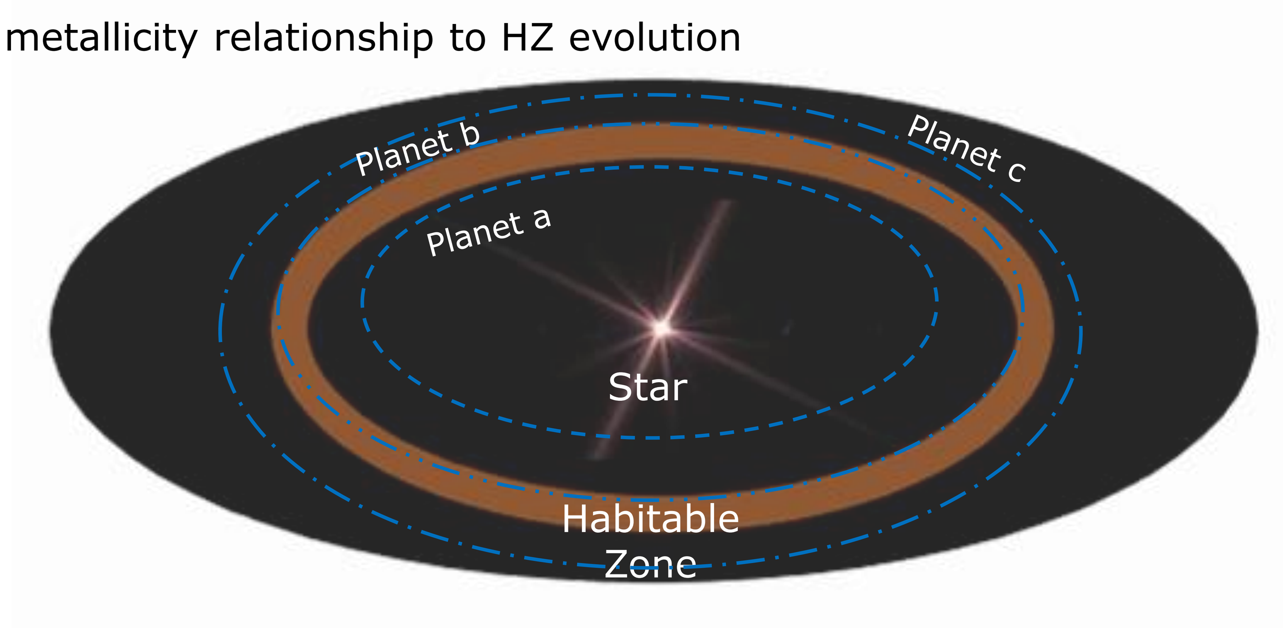

Figure 1: Schematic of habitable zone concept

Stellar Evolution & Habitable Zones:

The HZ is a measure of the potential for planetary habitability, defined here as the parametric region about a star in which surficial water is indicated to be stable on a planet.

This potential stability is a direct result of varying host star flux and effective radiative cooling mechanisms in accordance with the atmospheric greenhouse effect of orbiting planets [4].

The general consensus is that the majority of potentially habitable exoplanets are most likely to be orbiting FGKM-type host stars - favoured for their sufficient lifetimes, higher occurrence frequency, benign stellar radiative conditions, and wider HZs [5].

Data Modelling

Modelling 6 exoplanetary systems with FGK-type host stars with input parameters taken from the NASA Exoplanet Archive [6].

1 M☉ hypothetical stars generated with varying albedo and metallicity values based on existing systems.

Open source MESA-Web platform [7] used to model temporal host stellar evolution - output values then used to plot stellar evolutionary phases and corresponding HZ movements.

Adapted methods for HZ limit calculations:

- Effective Temperature Method [8,9]
- Insolation Method [10]

Key Points

- **Stellar evolution phases impart vital constraints on planetary habitability**
- **Habitable Zones (HZ) are theoretical indicators of planet habitability, limits calculated here using effective temperature and instellation methods**
- **Recommendations for habitability follow-ups: Tau Ceti e, HD 40307g, Kepler 62e and f**
- **Updated HZ boundaries serve as foundations for future mission target selection of modelled exoplanetary systems**
- **Closer inner HZ edge than in former estimates**

Results

Calculating the Zero Age Main Sequence point from stellar luminosity and H-burning luminosity outputs, we use existing planet orbital distance and age estimates to evaluate exoplanet positions within different HZ limits throughout pre and post-MS phases. We find that:

- Insolation (ins) HZ limits more generous than effective temperature method limits (eff) estimating higher population of habitable exoplanets
- Potential habitable exoplanets: **Tau Ceti e** (orbits within HZ in pre-MS, influencing current status), **HD 40307g** (orbits within HZ during main sequence phase), **Kepler 62e and f** (both considered habitable by at least 1 set of HZ limits)
- Marginal metallicity impact on habitability between the ranges 0.0001 to 0.001
- Albedo investigation redefines inner HZ edge distance estimates to 0.325 AU (from pre-existing 0.38 AU limit)

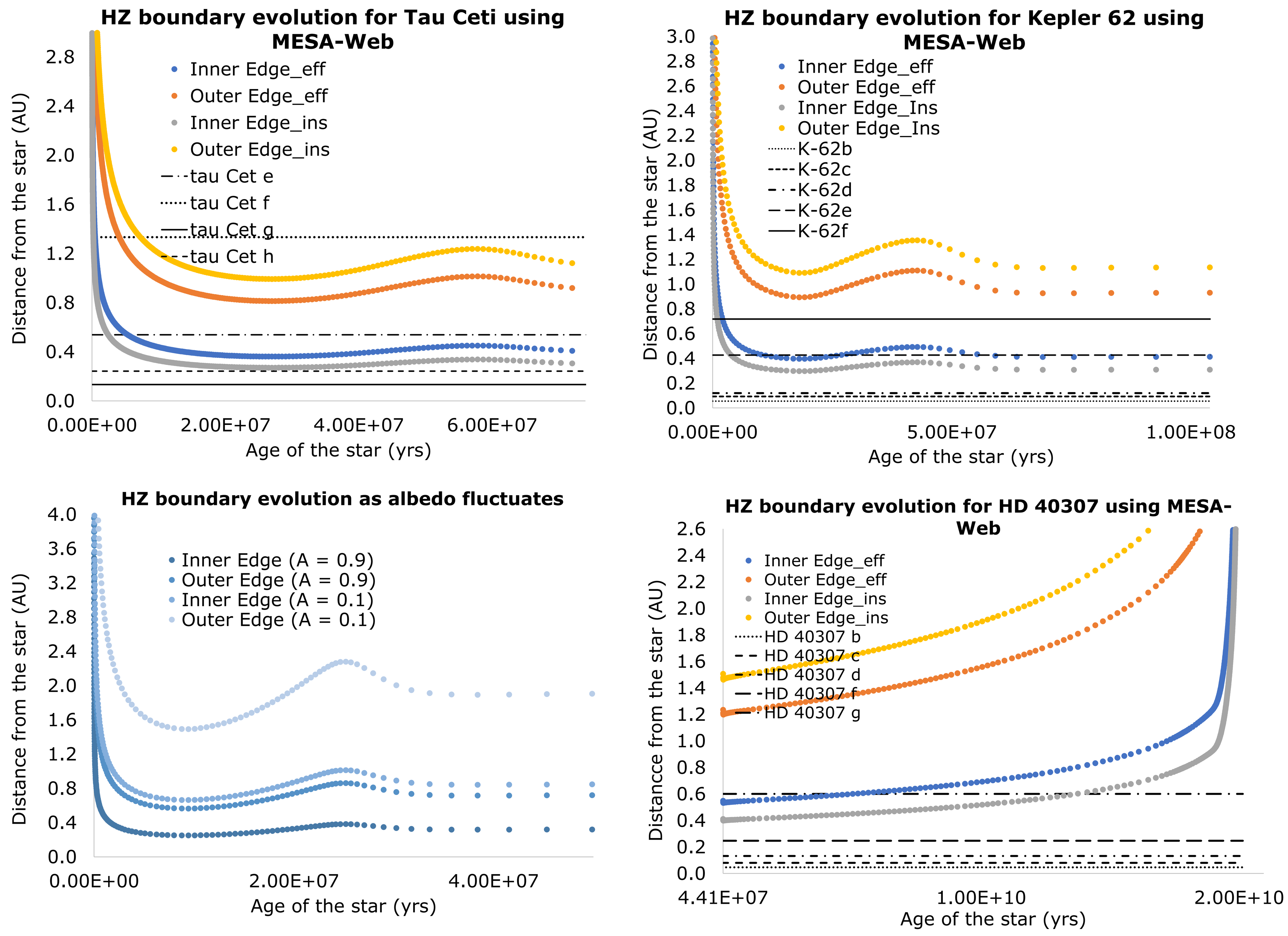

Figure 3 – HZ boundary limits over the modelled stellar lifetime with respective planet distances, to illustrate at which evolutionary phase these planets may be habitable.

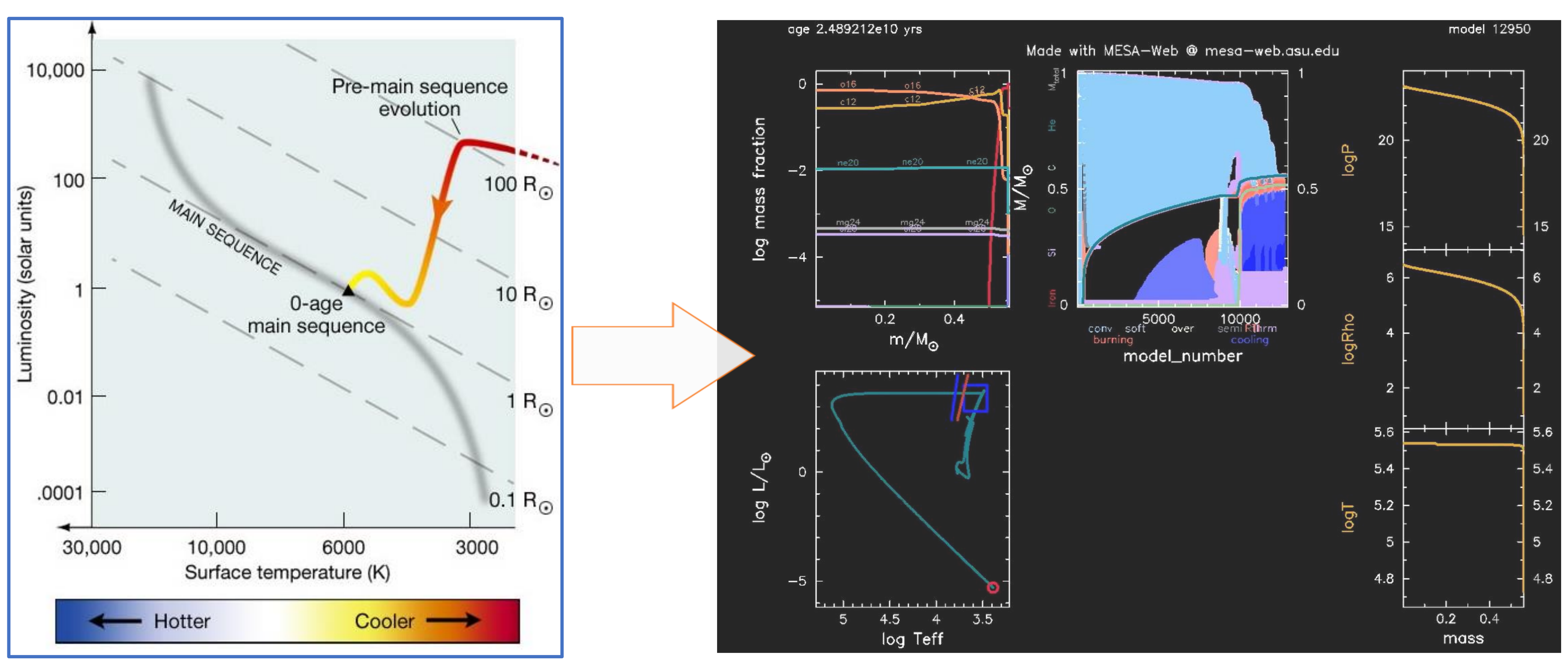

Figure 2a, b: Stellar evolutionary phases, simulation of 1M☉ solar metallicity (0.01) star (e.g., The Sun) from pre-main sequence to white dwarf with MESA-Web.
Sources: Penn State Astrophysics, MESA-Web

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