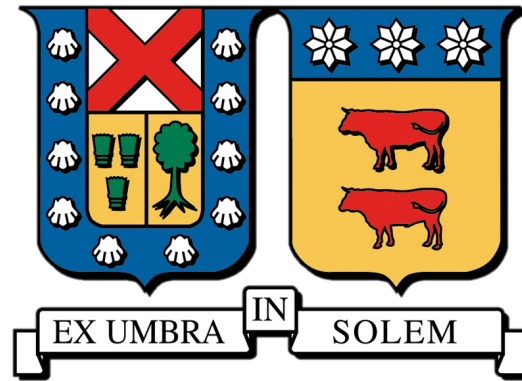


UNIVERSIDAD TÉCNICA FEDERICO SANTA MARÍA

PHYSICS DEPARTMENT



Navigating Stellar Evolution:  
Unraveling the Time Dependence of the Habitable Zone

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# Chapter 1

## Introduction

The discovery of the first planet orbiting a main sequence star in 1995 ([Mayor and Queloz, 1995](#)) other than the Sun has revolutionized astronomy. Following this discovery, awarded with the Nobel prize in physics in 2019, planet-hunting became one of the most exciting disciplines in astrophysics and new telescopes and instruments to more efficiently discover more exoplanets were built. Thanks to these efforts, we now know more than 5000 (reference e.g. webpage from NASA) exoplanets and can estimate that on average the Milky Way contains more than one planet per star.

The vast majority of all these planets have been discovered around sun-like main-sequence stars. This means that most planetary systems discovered so far will be affected by the evolution of their host star into a white dwarf. During the metamorphosis of a sun-like star into a white dwarf the conditions for planets orbiting this star dramatically change which, without any doubt, also affects their habitability.

I here perform a comprehensive exploration of the evolution of the habitable zones around sun-like main sequence stars. I will focus on the interplay of factors such as surface albedo variations or atmospheric reflection, as well as stellar temperatures and luminosities. I will use the equilibrium temperature framework to estimate the location of the habitable zone assuming black-body emission but also incorporating real white dwarf spectra. The evolution of the host star will in general be calculated with the Single Star Evolution (SSE) code ([Hurley et al., 2000](#)) but for comparison we also use the more accurate tracks provided by MESA ([Paxton et al., 2011](#)). I start this thesis with a brief summary of the evolution of a sun-like star.

### 1.1 Star and planet formation and stellar Evolution

Our principal objective is to visualize the evolution of the habitable zone as a main sequence star evolves. A summary of the evolution of a host star is provided in [Figure 1.1](#) for a star with one

solar mass on the main sequence.

Stars and planetary systems form from dense molecular clouds in the interstellar medium. These clouds consist mostly of hydrogen but approximately one percent of their mass is found in the form of small dust grains. If the mass of a molecular cloud exceeds the critical Jeans-mass, it collapses and fragments. Due to the conservation of angular momentum, not all the material can directly fall onto the central forming star and instead forms a circumstellar (often called protoplanetary) disk consisting of gas and dust. Planets form in these protoplanetary disks either through core-accretion or gravitational collapse.

After about ten million years, the temperature in the centre of the contracting star becomes sufficient to start hydrogen burning and the gas in the surrounding disk has been evaporated, leaving behind a planetary system and some debris. A mature planetary system around a main sequence star has formed.

With the beginning of hydrogen burning in its core, the star has entered the main sequence and started its longest evolutionary phase. During the main sequence the evolution of the star is driven by the nuclear time scale which corresponds to approximately 10 Gyrs for a star of one solar mass. During this time neither its structure nor its temperature change dramatically.

A solar like star on the main sequence has a radiative core and a small convective envelope for stellar masses below  $\sim 1.2$  solar masses. The smaller its mass, the deeper the convective envelope. Main sequence stars with masses exceeding  $\sim 1.2$  solar masses instead have a convective core and a radiative envelope. The luminosity of the star only slightly increases as the chemical composition in the core is gradually changing due to hydrogen burning.

The main sequence life of a star ends when the **Hydrogen core is exhausted**. The star continues hydrogen burning in a shell around the central helium core. The helium core contracts thereby releasing gravitational energy really fast. The shell expands and cools down. This phase is called the sub-giant branch.

Due to the expansion, the envelope becomes more and more convective until the star reaches the Hayashi track in the HR-diagram right of which no hydrostatic solutions exist. The compact core supports the shell burning and the luminosity of the star increases while its temperature remains nearly constant. The star is on the first giant branch. The deep outer convection zones reach the hydrogen burning shell and transport the products of the burning process to the surface (**first dredge up**). The core continues to contract and the temperature rises until it becomes sufficiently hot for helium fusion to begin which defines the end of the first giant branch.

Helium fusion occurs through a process called the triple-alpha process, where three helium nuclei (alpha particles) combine to form carbon. During helium core burning the star contracts and heats up while its luminosity remains nearly constant. As the star moves to the left in the HR diagram during core-helium burning this phase is often called the horizontal branch.

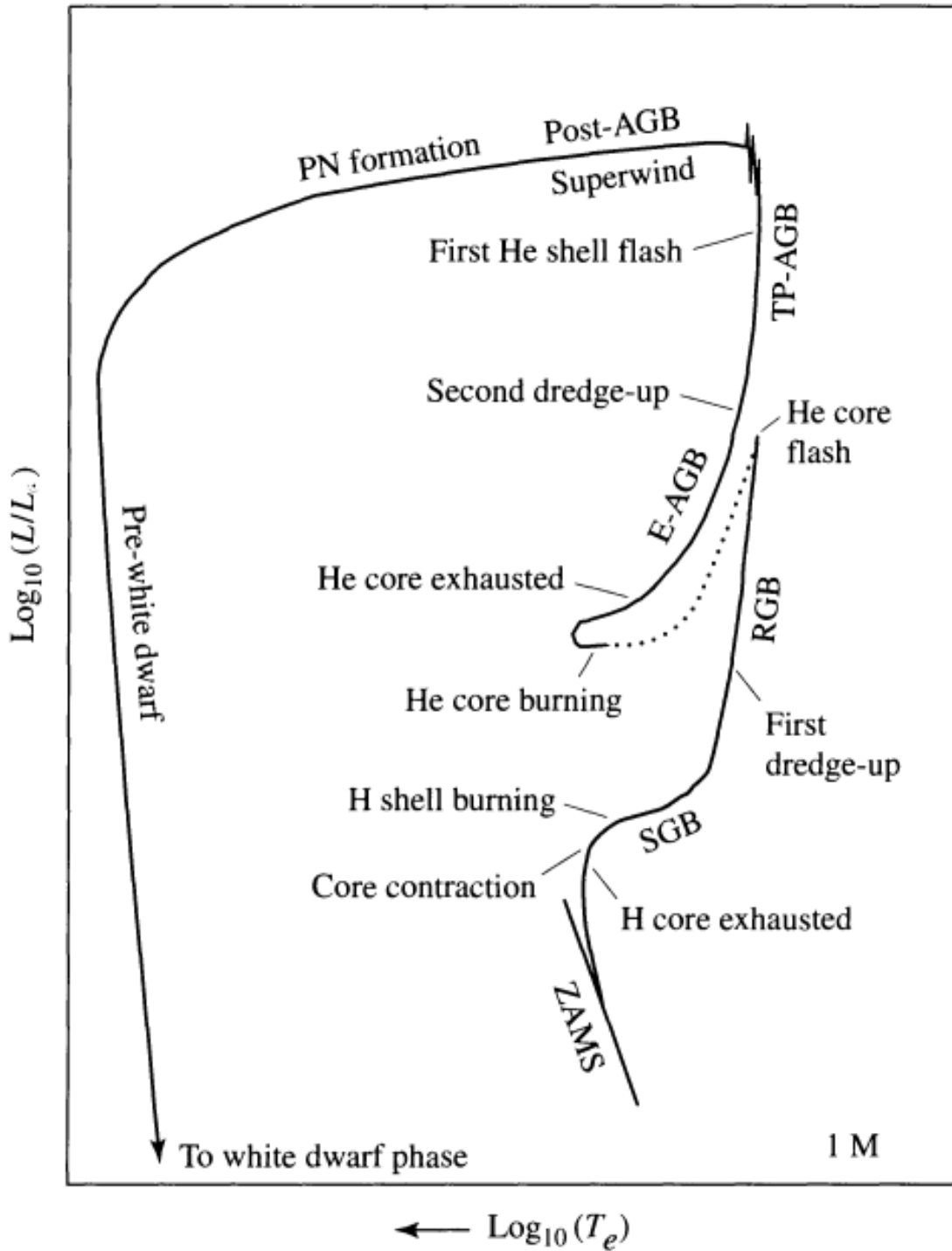


Figure 1.1: This Hertzsprung-Russell (HR) diagram illustrating the evolutionary journey of a 1 solar mass star, showcasing its luminosity and temperature across different stages of its life. The plotted points correspond to key phases in the stellar lifecycle, each labeled for clarity.

Once the Helium core is exhausted, it starts burning in the shell around an inner Carbon Oxygen core. The star again cools and expands and asymptotically approaches the Hayashi track. The star is on the asymptotic giant branch (AGB). There's a **Second Dredge Up** and at the very end of the evolution, the star produces **Thermal Pulses** during which the star periodically produces **Helium Shell Flashes**. During these flashes, the outer layers expand and then contract, that is, the radius of the star is dramatically changing. Intense stellar winds, driven by radiation pressure and pulsations, result in substantial mass loss from the outer layers of the star.

At the end of the AGB, the envelope around the carbon/oxygen core is expelled. The mass loss creates an outer layer of ionized gas around the star called the **Planetary Nebula**. The carbon-oxygen core is unable to trigger more fusion and instead forms a stellar remnant called a **White Dwarf**.

In the absence of fusion, the pressure keeping a star in hydrostatic equilibrium is replaced by electron degeneracy. White dwarfs are small objects, approximately the size of the Earth, and simply cool with time. After the planetary nebula phase, white dwarfs are very hot, that is, their effective temperature easily exceeds 100 000K. As no energy except for slow contraction is available to white dwarfs (and this energy is used to increase the Fermi energy), their temperature and luminosity decrease with time. The oldest white dwarfs in our Galaxy have effective temperatures of just  $\sim 3000 - 4000\text{K}$ .

## 1.2 Simulating stellar evolution

In order to predict the evolution of the habitable zone it is required to know the evolution of the radius and the effective temperature of the central star. In this work, I used two different codes that are able to predict the evolution of sun-like stars.

### 1.2.1 Single Stellar Evolution (SSE)

SSE is a stellar evolution code that uses an analytic fitting formula to quickly and still reasonably well predict the evolution of a main sequence star with a given mass and metallicity. SSE generates "evolutionary tracks" that describe the changes in key star properties such as temperature, radius, and luminosity.

One of the biggest advantages of SSE is its computational speed. SSE provides all the necessary information in seconds, which is helpful in case one wants to evolve stars covering a large range of initial conditions. SSE is therefore the default code I used for the work presented in this thesis. However, we also compare the predictions for the evolution of the habitable zone calculated with SSE with simulations based on the more accurate stellar evolution code MESA which will be briefly

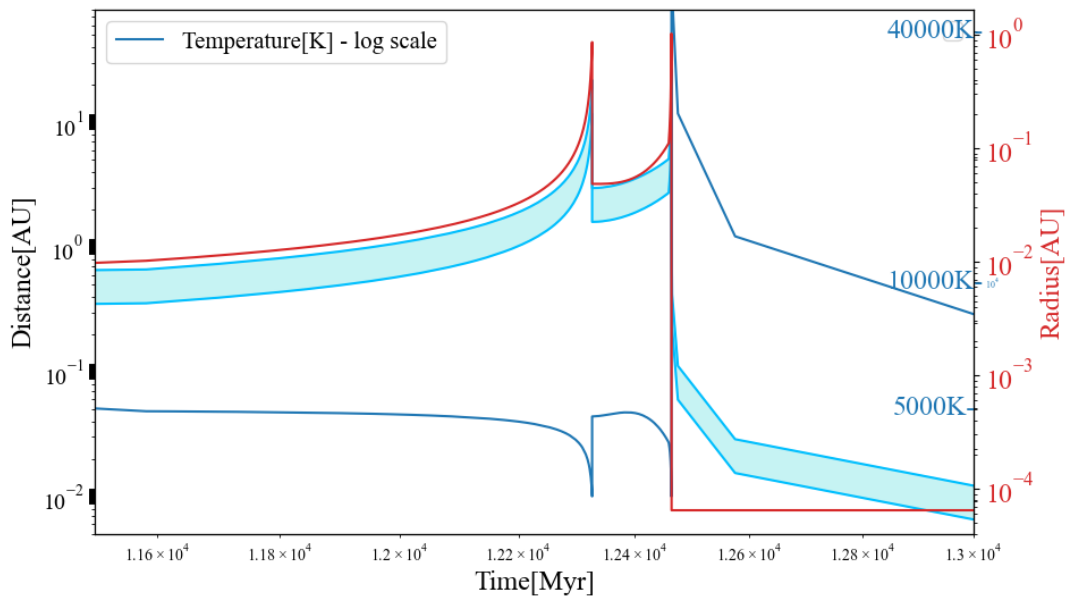


Figure 1.2: This dynamic plot captures the temporal evolution of a 1 solar mass star, charting its luminosity (yellow curve), temperature (blue curve), and the radius of its core (red curve) over time. Each labeled stage corresponds to distinct phases in the star's lifecycle, unraveling the intricate interplay between luminosity, temperature, and core radius.

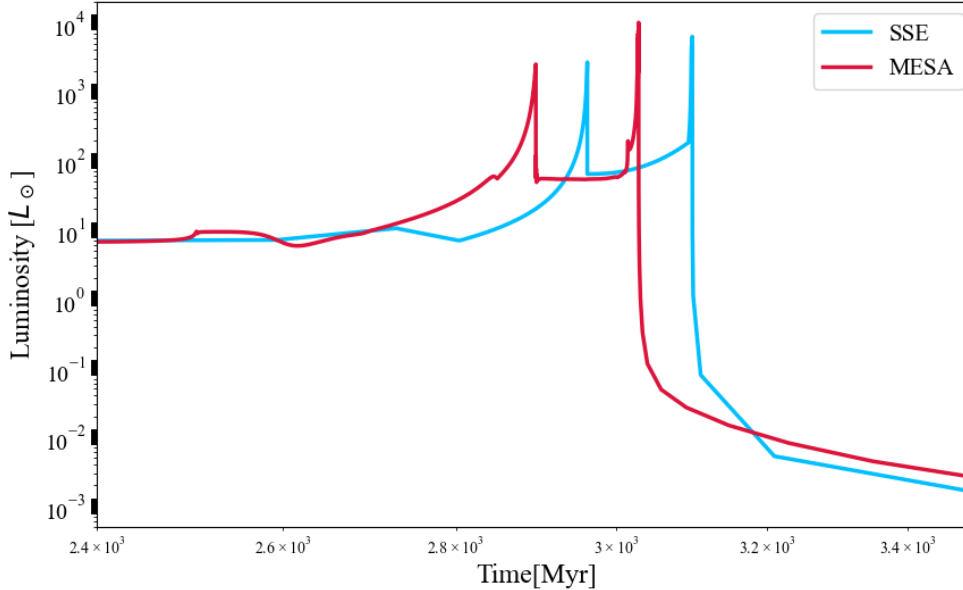


Figure 1.3: This plot contrasts the evolutionary tracks of a 1.5 solar mass star simulated using the SSE (blue curve) and MESA (red curve) codes. The initial conditions are consistent between the two simulations. The axes represent the star’s luminosity over time, offering a side-by-side comparison of the stellar evolution as modeled by SSE and MESA.

described in what follows.

### 1.2.2 Modules for Experiments in Stellar Astrophysics (MESA)

MESA was developed by a collaborative team that included scientists from the University of California, Santa Barbara (UCSB), the University of Arizona, and Stony Brook University, among others. MESA is a highly modular code that allows researchers to include a wide range of physical processes and modules in their simulations. It incorporates detailed treatments of nuclear burning, convection, mixing, and other relevant physical phenomena. MESA is designed to handle multi-dimensional simulations, which allows a more realistic view with advanced models of physics processes.

In contrast to SSE, MESA solves the differential equations describing stellar evolution in each time step. Therefore MESA requires much longer computing times than SSE. For a general understanding of the evolution of the habitable zone, SSE is clearly sufficient. Nevertheless, to estimate the impact of more precise stellar evolution models, we compared the predicted evolution using SSE and MESA. In Figure 1.3 we illustrate the luminosity evolution of a 1.5 solar mass star with MESA and with SSE.

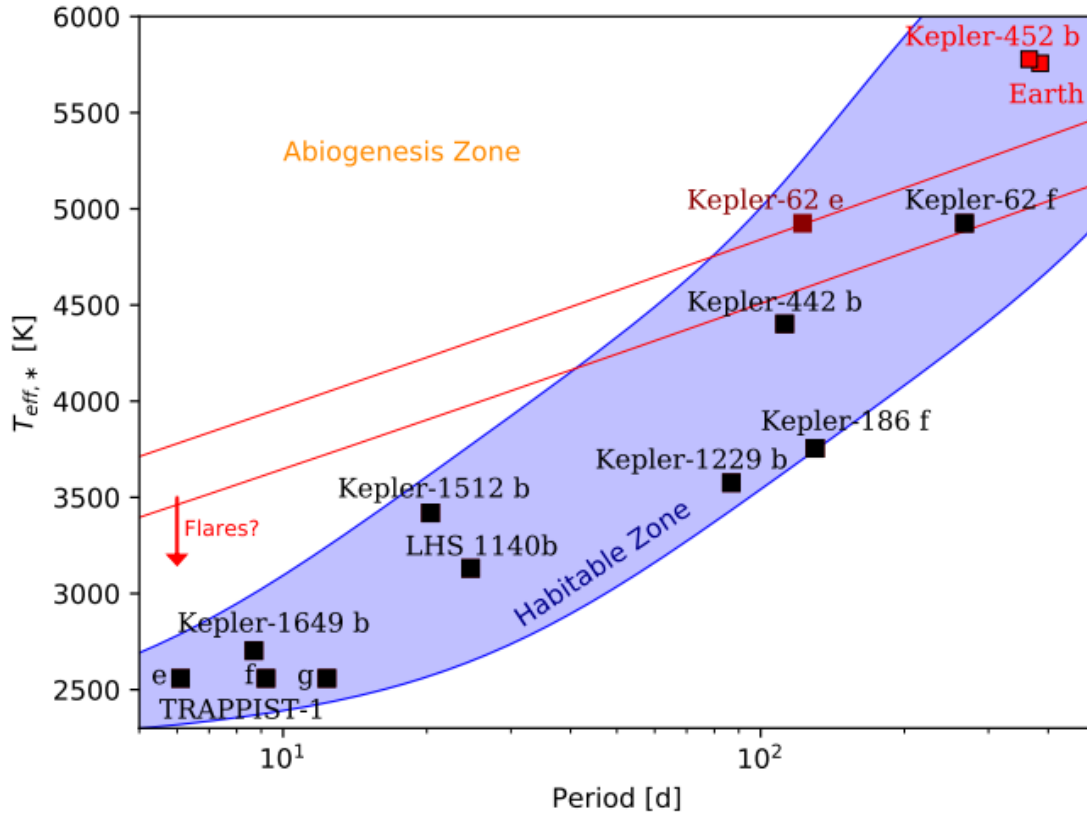


Figure 1.4: Figure taken from (Rimmer et al., 2018). The ‘abiogenesis zone’ indicates where the stellar UV flux is large enough to result in a 50% yield of the photochemical product. The red region shows the propagated experimental error. The liquid water habitable zone is also shown in blue and the Exoplanets are on it.

### 1.3 The generation of life, the habitable zone, and exoplanets

In the last decades, the discoveries of exoplanets and planetary systems have increased exponentially. One of the main questions driving planetary research is whether life exists in other worlds or not. In the quest to answer if life exists beyond Earth, it is of fundamental importance to establish life-sustaining conditions.

When thinking about life on Earth, there is one fundamental condition for life to exist: liquid water. At sea pressure, the temperature range for the water to exist in a liquid state is around 0[°C] to 100[°C].

For the generation of life, however, liquid water alone is not sufficient. The macromolecular building blocks of life were likely produced photochemically in the presence of ultraviolet (UV) light, which implies that life can only be generated around stars that produce sufficient UV radiation for this photochemistry. This is illustrated in Fig. 1.4.

## 1.4 Equilibrium Temperature

The most important condition to sustain life as we know it is the presence of liquid water. To estimate whether a planet might have liquid water on its surface, it is therefore of fundamental importance to estimate its temperature. The simplest way to estimate the temperature of a planet is to calculate its equilibrium temperature.

We can imagine a system in the cosmos, of a single star and a single planet. The star is fitted as a Black Body Spectrum, and we can estimate the amount of flux emitted by the star as follows:

$$F_{star} = \sigma T_{star}^4 \quad (1.1)$$

In terms of the luminosity of a star, this can be rewritten:

$$L = 4\pi R_{star}^2 \sigma T_{star}^4 \quad (1.2)$$

A planet orbiting a star at a certain distance is hit by a fraction of the radiation emitted by the star. Assuming that a fraction of the incoming radiation is reflected and the remaining part of the energy is thermalized and re-emitted by the planet in the form of black body radiation, it is possible to estimate the temperature of the planet. This temperature is called the equilibrium temperature because it assumes a perfect balance between the energy supplied by the star and the radiation emitted by the planet, that is,  $F_{abs} = F_{emitted}$ . According to this assumption, the equilibrium temperature is given by:

$$T_{eq} = \left( \frac{L(1 - A_B)}{16\sigma\pi a^2} \right)^{1/4}. \quad (1.3)$$

Here, the variable  $a$  represents the orbital distance under consideration, and  $A_B$  is the fraction of energy reflected by the planet, called the albedo.

We can now define the most simple habitable zone as a distance from a given star where the equilibrium temperature is between zero and hundred degrees Celsius. Thus, we determine the specific value of  $a$  at which a planet could maintain a temperature allowing for liquid water to exist.

$$a_{habitable} = \frac{\sqrt{L(1 - A_B)}}{4T_{eq}^2\sqrt{\sigma\pi}}, \quad (1.4)$$

with  $T_{\text{eq}} = 273 - 373\text{K}$ . Once we have the temperatures and luminosities of the star through time, we can calculate a range of distances from the star that corresponds to the Habitable Zone, a location where a planet could sustain life like ours. A key parameter in the above calculation is the albedo ( $A_B$ ) and we therefore discuss its possible values in more detail in what follows.

## 1.5 The Albedo

As mentioned in the equation above, albedo corresponds to the percentage of incident light that is reflected by the surface. When the planet receives the flux emitted by the star, part of it is absorbed by the planet warming it, and the other part is reflected. A planet that reflects most of the light will not be warmed up easily, so it will need to be closer to the star to reach the temperature required for liquid water to exist.

The reflection of a planet is different depending on the different materials covering the planet's surface. As described in [Whittaker et al. \(2022\)](#) the albedo is not the same depending on the color and composition of its surface. In addition, the albedo varies with wavelength and therefore might evolve depending on the stellar state.

## 1.6 The impact of the atmosphere

The equilibrium temperature described in the previous section is simplistic and does not include the impact an atmosphere can have on the temperature of a planet. Certain gases and particles in the atmosphere of a planet can absorb specific wavelengths of light in certain amounts.

For example, the Ozone of the Earth's atmosphere absorbs nearly all UV rays from the sun which is crucial for life on Earth as UV radiation can be harmful to humans. Some wavelengths are absorbed more by the atmosphere than others, which leads to the famous greenhouse effect.

While the optical light from the sun can pass the atmosphere, Greenhouse gases, such as carbon dioxide ( $CO_2$ ) and water vapor, selectively absorb certain wavelengths of infrared radiation emitted by the Earth's surface. This absorption contributes to the greenhouse effect, trapping heat in the atmosphere and increasing Earth's surface temperature compared to the equilibrium temperature.

A detailed consideration of the effects of the atmosphere is far beyond the scope of this thesis. However, we will discuss to some degree how an atmosphere might impact the evolution of the habitable zone.

# Chapter 2

## The evolution of the habitable zone

The evolution of the star's radius and temperature, which together determine the evolution of its luminosity, determine where a planet could sustain liquid water at each evolutionary stage. This habitable zone is defined as the region where the equilibrium temperature remains within the range of  $0[^\circ\text{C}]$  to  $100[^\circ\text{C}]$ . As the star evolves, the location of the habitable zone evolves as well. In what follows I describe the general evolution of the habitable zone, discuss the impact of assumptions concerning the albedo, and the potential impact of an atmosphere as well as the spectral emission of white dwarfs.

### 2.1 The default model

As a basic initial model, I calculate the equilibrium temperature of a planet orbiting a one solar mass star, calculate the evolution of the star with SSE, assume the emission of the white dwarf to be represented by a blackbody, and consider a constant albedo of  $A_B = 0.5$ . The resulting evolution with time of the habitable zone is shown as the shaded region in Figure 2.1.

During the main sequence evolution of the star, the habitable zone slightly moves to larger distances as the luminosity of the star increases. As soon as the star leaves the main sequence, during the giant and the sub-giant branch, the luminosity of the star increases by several orders of magnitude. As a consequence, the habitable zone moves from the order of  $\sim 0.5 - 1$  astronomical units to several tens of au. When helium burning starts, the star's luminosity decreases and as a consequence, the habitable zone moves back closer to the star, down to a few astronomical units. After most of the helium in the core has been consumed, the star expands again, entering the AGB. The increased luminosity causes the habitable zone to again move to larger distances, that is, up to several tens of astronomical units. This means that for the solar system, the ice giants Uranus and Neptune will be located close to the habitable zone when the sun has become a giant. At the end of the AGB, the envelope of the star is expelled and the central object of the planetary

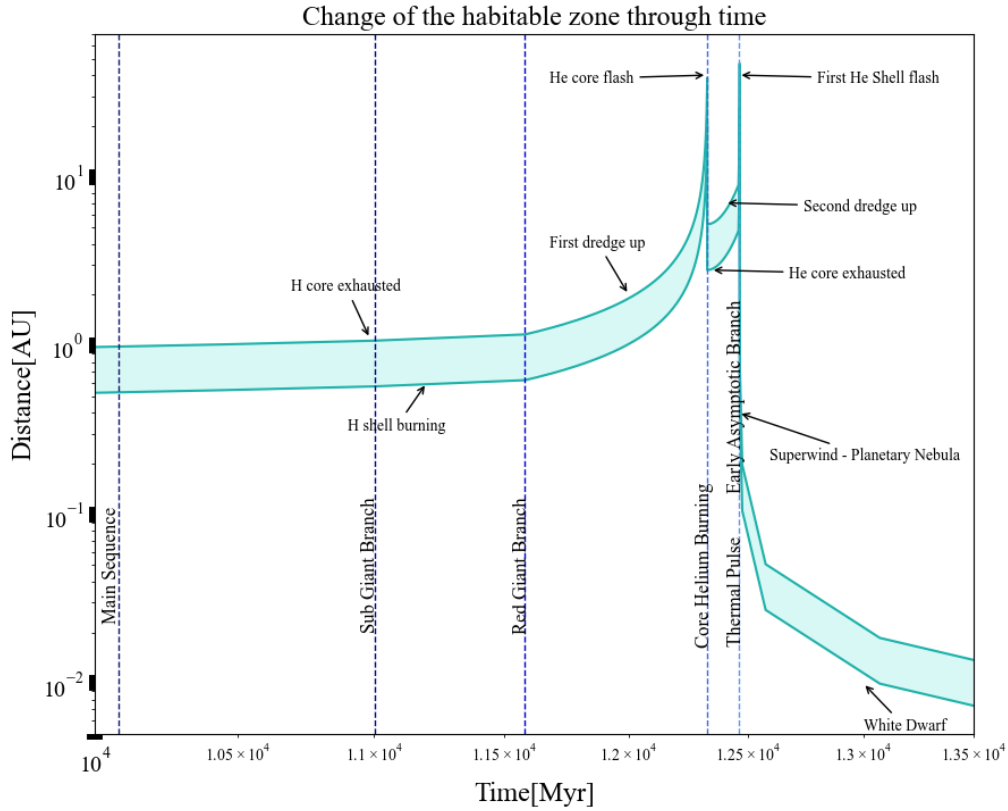


Figure 2.1: This plot traces the temporal evolution of the habitable zone around a 1 solar mass star over its lifecycle. The habitable zone, depicted by the colored zone, represents the region where temperatures allow for the potential existence of liquid water. As the star progresses through various stages of evolution, marked by distinct labels, the habitable zone dynamically adjusts.

systems is the burned-out core of the AGB star, a stellar remnant called a white dwarf. This initially very hot core quickly cools and as a consequence, the habitable zone once again moves closer to the star. As the white dwarf cooling proceeds very fast at the beginning, this decrease in distance of the habitable zone is especially fast immediately after the white dwarf formation and subsequently slows down. When the evolutionary time of the star becomes close to the Hubble time, the habitable zone is located ten thousand times closer to the star than during the main sequence.

## 2.2 Dependence on stellar mass

Maintaining our standard model with unchanged initial conditions, we aim to assess the extent to which the habitable zone fluctuates based on variations in the initial stellar mass. This time the

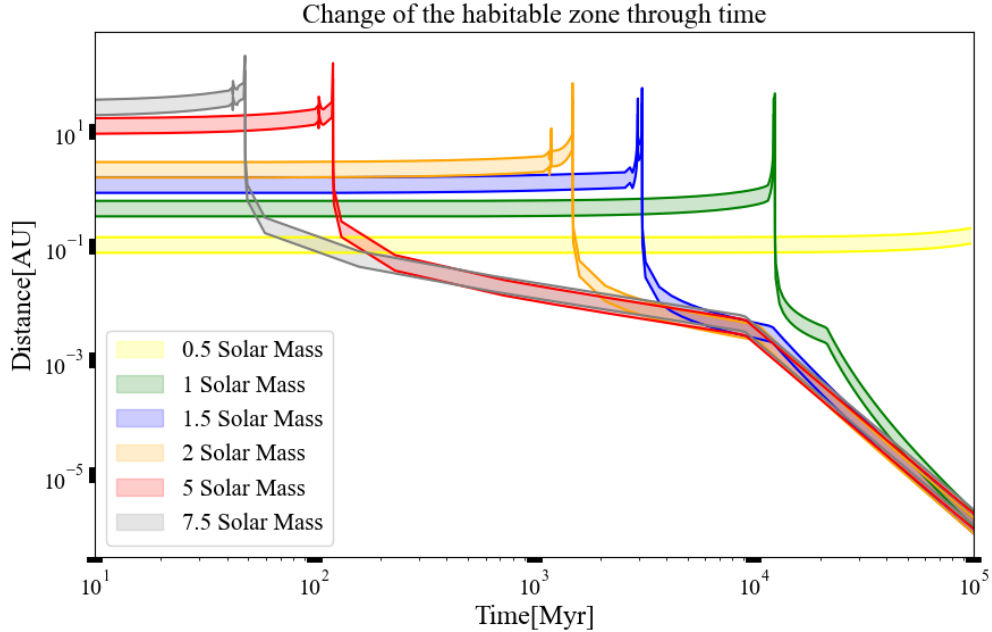


Figure 2.2: This plot illustrates the evolution of the habitable zone around stars within a mass range of 0.5 to 7.5 solar masses. Each stellar mass is represented by a distinct color, showcasing how the habitable zone’s distance changes over time as the stars progress through various evolutionary stages. The main differences generated by changes in the initial stellar mass are the changes in luminosity (larger masses require a larger distance for a planet to maintain in the habitable zone) and evolutionary lifetime on the main sequence which is shorter for larger masses.

SSE program was run for masses spanning from 0.5 [ $M_{\odot}$ ] to 7.5 [ $M_{\odot}$ ]. The corresponding evolution of the habitable zone with time is shown in Figure 2.2.

This gives us the insight that the habitable zone of each star is displaced closer or further depending mainly on the star’s mass. It makes sense since more massive stars are bigger in size and hotter and a larger distance is needed to maintain an equilibrium temperature that permits the existence of liquid water. In what follows we mostly focus on evolutionary models for a star of one solar mass to investigate the importance of change of other parameters.

## 2.3 A more realistic approach for the albedo

In our default model, the albedo is simply a constant which is hardly realistic as the fraction of reflected light from a surface depends on the wavelength and thus also on the temperature of the star which is changing throughout its evolution. To enhance the accuracy of our habitable zone calculations, we investigate in this section the impact of different values and models of the albedo.

We first investigate the influence of different but constant values of the albedo. The results

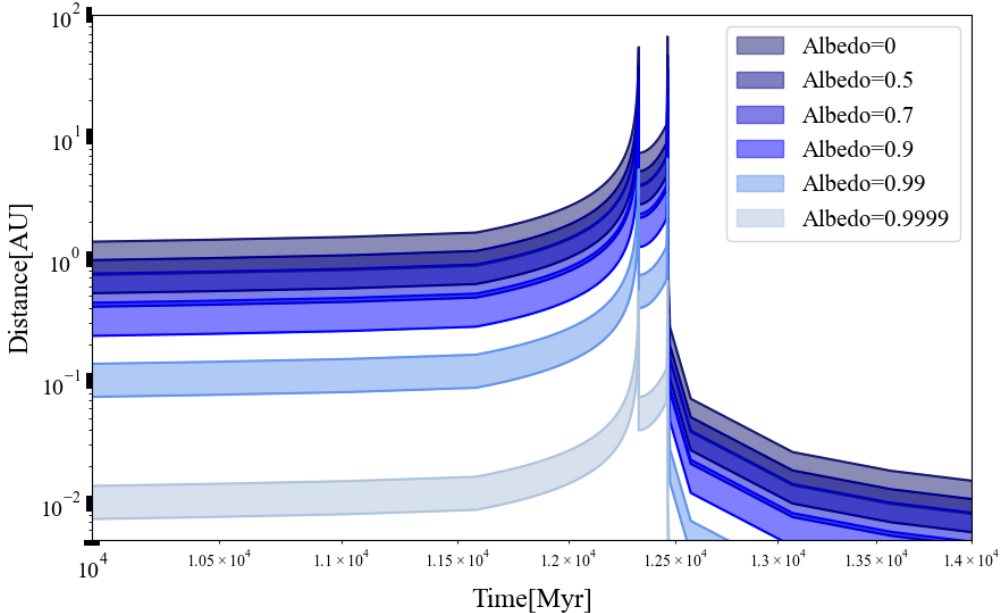


Figure 2.3: A visual representation of how the habitable zone’s location (in AU) changes with the passage of time [Myr] as a star of  $1[M_{\odot}]$  undergoes its evolution. The different albedos are portrayed in various shades of blue. The larger the albedo, the closer a planet needs to be to maintain liquid water.

are shown in Figure 2.3 for the habitable zone around a sun-like star. We notice that between the albedos from 0 to 0.9, the habitable zone goes around  $0.1[\text{AU}]$  to  $1[\text{AU}]$ . For values of the albedo closer to 1 the habitable zone is lower than  $0.01[\text{AU}]$ , which is really close to the star. This is because most of the radiation is reflected, and only a small fraction of the energy that is provided by the star heats up the planet.

As mentioned above, it is important to consider that the albedo varies with wavelength. In order to understand the impact of the wavelength dependence of the albedo, we need to consider how the emission of a star is changing during its evolution. In Figure 2.4 the spectrum of a black body of the temperature of the current Sun is shown. Most of the radiation is emitted at visual and infrared wavelengths and only a small fraction of energy is emitted in the UV and EUV.

In contrast, soon after the planetary nebula phase when the core of the giant, the future white dwarf, starts to dominate the emission, the spectrum is dominated by high-energy radiation. The just-exposed cores of giant stars typically have temperatures of  $10^5[\text{K}]$ . As shown in Figure 2.5, a black body of such high temperatures indeed emits mostly UV and EUV radiation.

In order to take into account the changes in the spectral energy distribution during stellar evolution, we considered albedos corresponding to a snow surface (Gallet et al., 2011) as well as those suitable for metal-rich surfaces (Hu et al., 2012). The comparison between those albedos

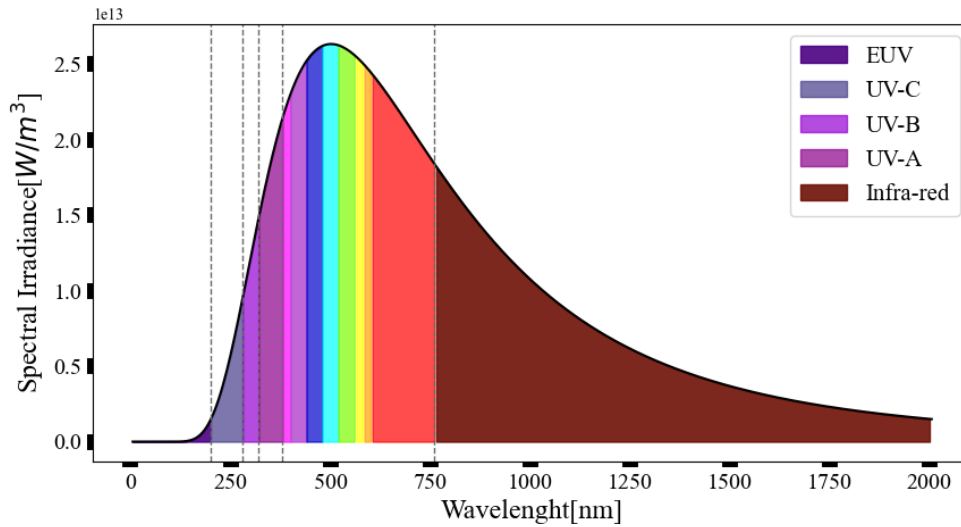


Figure 2.4: This plot depicts the black body radiation spectrum of a sun-like star with a temperature of 5777K. The spectrum is color-coded to highlight different zones corresponding to specific wavelengths. The emission of the sun is dominated by optical and infrared radiation and only a relatively small part of the Sun’s emission is emitted in the form of high energy radiation.

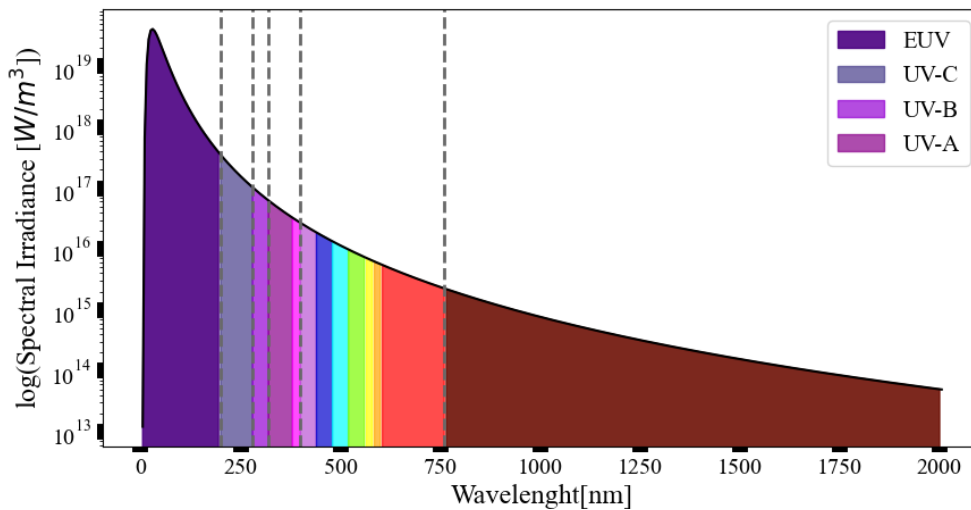


Figure 2.5: This plot depicts the black body radiation spectrum of a sun-like star after the envelope has been expelled and the young proto-white dwarf has a temperature of  $10^5$ K. The spectrum is color-coded to highlight different zones corresponding to specific wavelengths. During this stage of evolution, the emission is largely dominated by high-energy radiation.

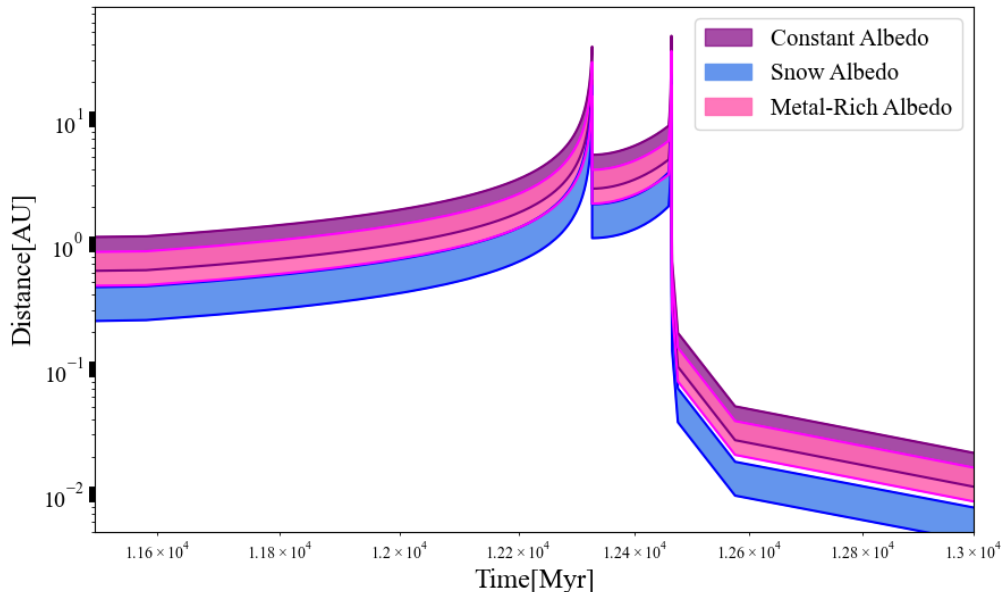


Figure 2.6: This plot illustrates the evolution of the habitable zone around a one solar mass star, considering different surface albedos. The habitable zones for a metal-rich surface, snow surface, and a constant albedo are depicted.

and the constant albedo from the previous section(0.5) is depicted in Figure 2.6. The mean albedo of snow is 0.98 until 900[nm]. At longer wavelength, it decreases sharply to values  $\sim 0.3$ . For metal-rich surfaces, the albedo is typically around 0.1, varies very little with wavelengths, and never exceeds 0.2. As we could not find tabulated values of both albedos in the literature, we used figures from the above-mentioned works and estimated average values of the albedo for each wavelength range illustrated in Fig. 2.4 and Fig. 2.5.

The varying albedos influence the temperature range suitable for habitability, showcasing how surface characteristics play a pivotal role in shaping the boundaries of the habitable zone across stellar evolution. However, the general evolution of the habitable zone is little affected by the wavelength dependence of the albedo. Only at one particular point during the evolution of a star, it affects for a relatively short period of time, the general trend. During the planetary nebula phase, when the cool envelope of a giant star is expelled and the hot core is exposed, the emitted spectrum changes from being dominated by infrared and optical emission (big and cool giant star) to being dominated by EUV radiation (the small and hot core of the giant). While the luminosity remains nearly constant during this phase, assuming a surface covered with snow, which reflects most of the high energy radiation, the spectral change causes the habitable zone to move closer to the star. This effect is shown in Fig. 2.7.

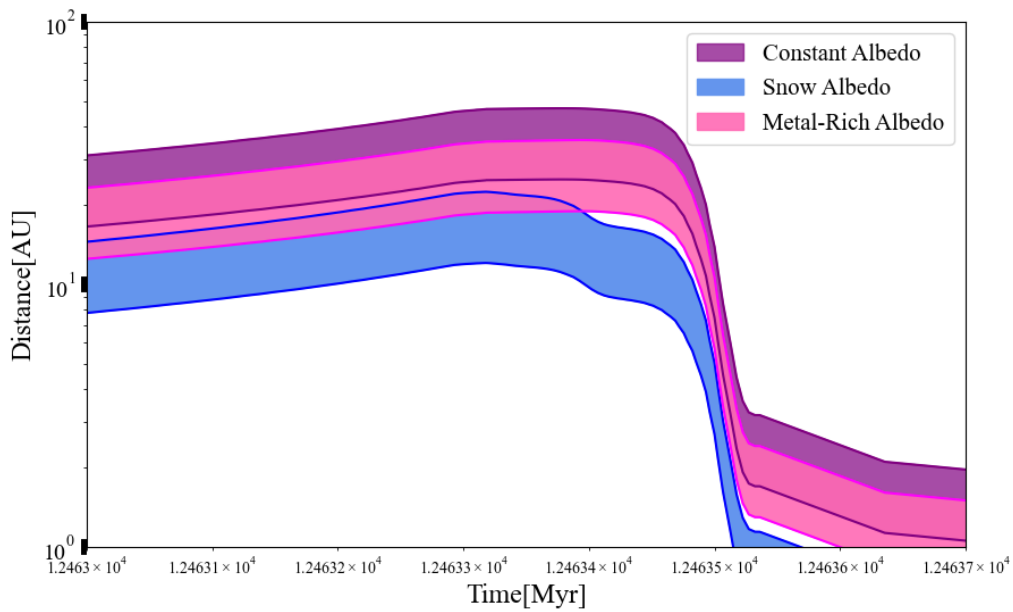


Figure 2.7: Following the AGB, during the planetary nebula phase, the spectral emission of the star switches from being dominated by energy radiation to consisting mostly of high energy radiation while the luminosity remains nearly constant. For a constant albedo (purple), this does not affect the location of the habitable zone. For a surface covered with snow, however, the habitable zone moves closer to the star as a significant fraction of energy hits the planet in the form of high-energy radiation which is more efficiently reflected.

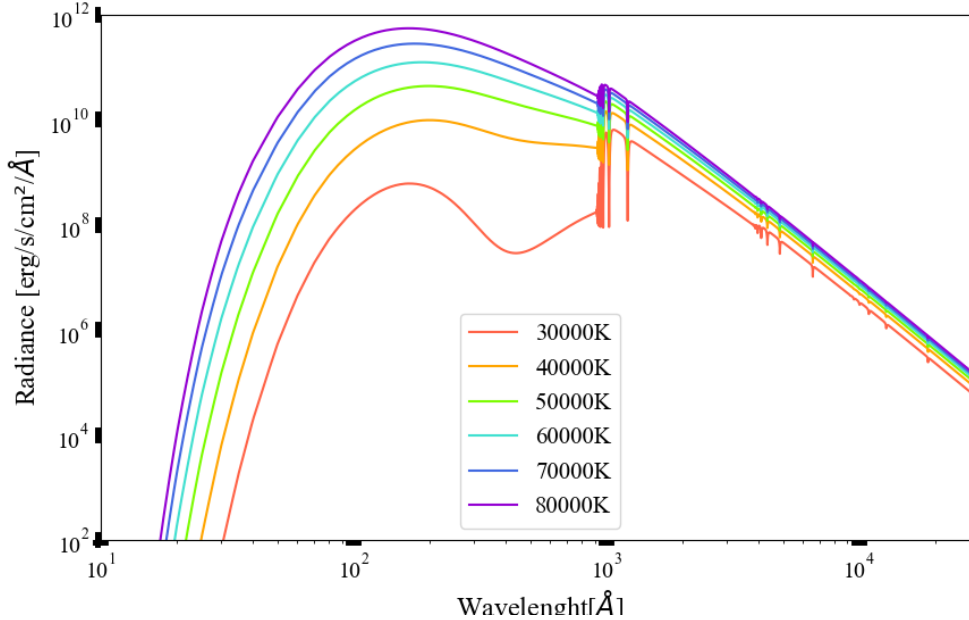


Figure 2.8: This plot juxtaposes the habitable zones computed using white dwarf model spectra, varying with temperature, with those derived from a black body model and assuming an albedo corresponding to surfaces covered with snow. The effect is relatively small which illustrates that for an order of magnitude estimate the assumption of black body radiation is acceptable at least for white dwarfs.

## 2.4 Incorporating Real White Dwarf Spectra

In the previous section, we have calculated the evolution of the habitable zone assuming black-body spectra. This, of course, represents a rough approximation of reality. Stars are usually not black bodies but host an optically thin atmosphere above the photosphere which causes the appearance of spectral absorption lines which affects the spectral energy distribution. We illustrate this effect by comparing the position of the habitable zone by replacing black body emission with model spectra for white dwarfs of different temperatures. The spectral energy distribution of model white dwarf spectra from Koester is shown in Fig. 2.8. from Koester, with a range of for temperatures ranging from 30000[K] to 80000[K], all for a white dwarf of  $\log(g) \approx 7.5$  (which is representative of the remnant of a one solar mass star). We considered an albedo corresponding to a surface covered with snow to calculate the habitable zone using the spectra and our black body model displayed in Fig. 2.9. The small differences between habitable zones calculated with model spectra and assuming black body radiation are caused by the redistribution of emitted flux due to the presence of a hydrogen-rich atmosphere.

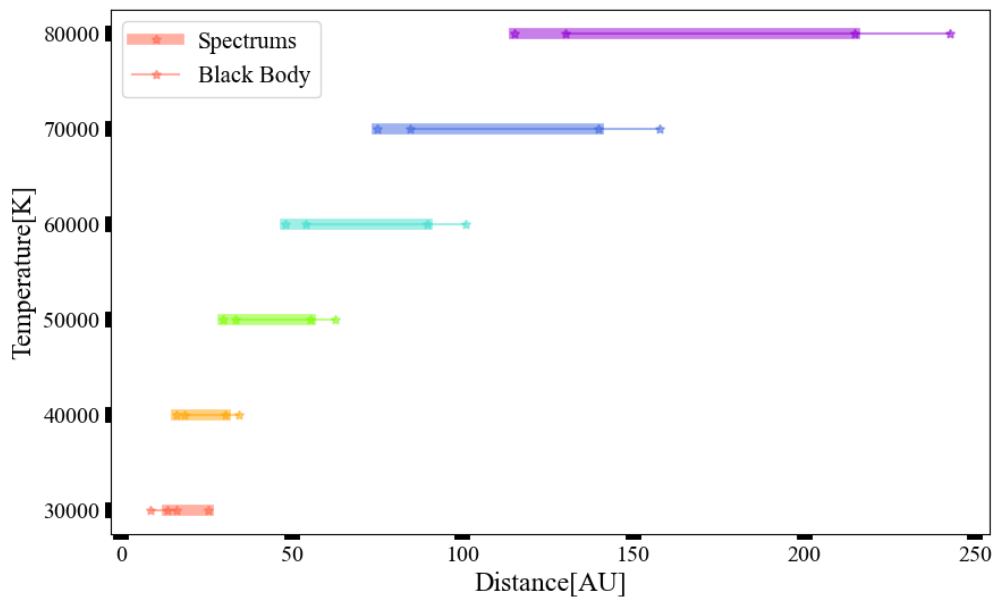


Figure 2.9: This plot juxtaposes the habitable zones computed from actual white dwarf spectra, varying with temperature, with those derived from our black body model. The comparison offers insights into the potential disparities between real observational data and the theoretical predictions of the black body model for habitable zones around white dwarfs.

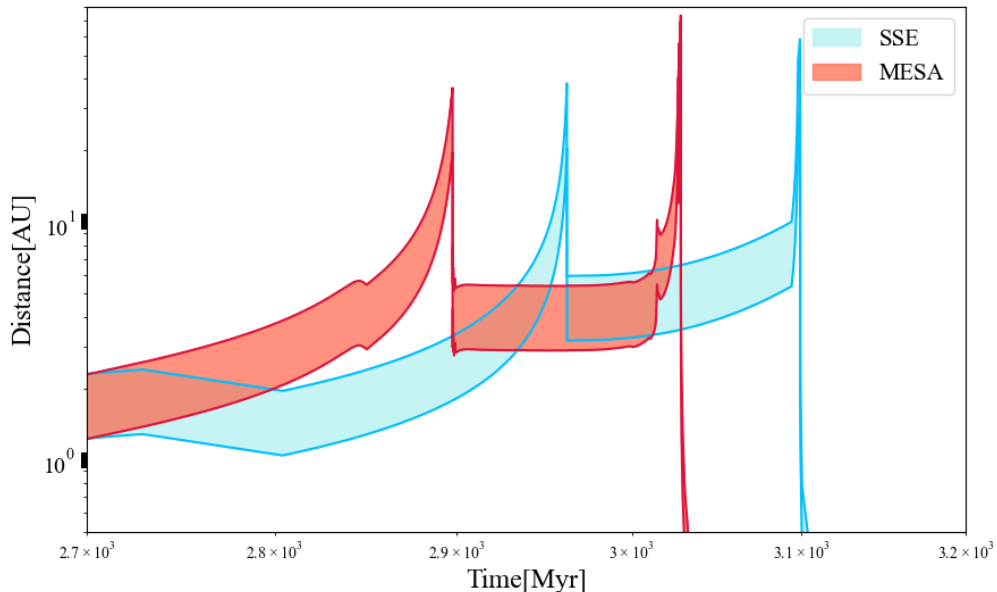


Figure 2.10: This plot juxtaposes the habitable zone evolution for a 1.5 solar mass star with a constant albedo of 0.5, as modeled using data collected from both MESA and SSE simulations. In general, the evolution is the same.

## 2.5 More accurate stellar evolution models

As we mentioned earlier in 1.2, there are quite some differences in the simulations of a star between SSE and MESA codes. With the data gathered in Figure 1.3, we calculate the habitable zone of both codes to check their differences. Most parts of the evolution are well represented by the simpler code SSE. However, at the end of the AGB, stars evolve through thermal pulses generated by helium shell flashes. During these pulses the temperature and size of the star change on relatively short time scales which also affects the habitable zone. This effect is shown in Fig. 2.10.

## 2.6 The impact of the atmosphere

So far we have fully ignored a very important part of the generation of life and the real temperature of a planet: planetary atmospheres. The presence of an atmosphere has been acknowledged to impact the radiation reaching a planet. In a simplified approach to model this effect, we will account for the Earth's atmospheric transmittance and incorporate it into the albedo. Specifically, for UV radiation, where there is negligible transmission, the albedo will approach unity, indicating minimal absorbance. This simple effect of an atmosphere would lead to a decrease in the distance at which a planet might be habitable as depicted in Fig. 2.12 for a metal-rich surface.

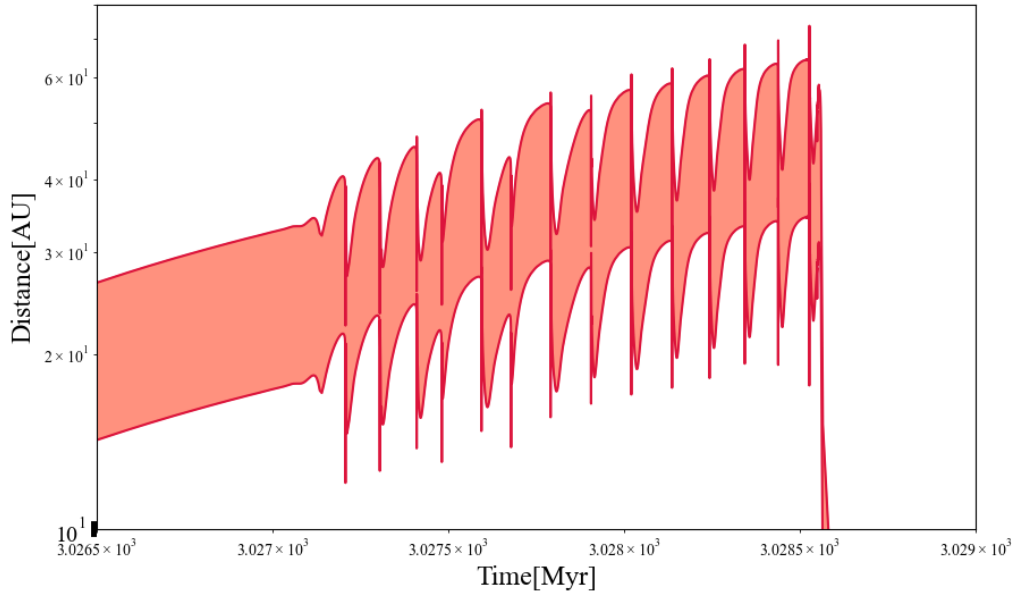


Figure 2.11: Zooming into the end of the AGB, we see the thermal pulses during the late AGB phase. These pulses cannot be reproduced by a simple code as SEE that uses approximations but is predicted by more accurate stellar evolution codes such as MESA.

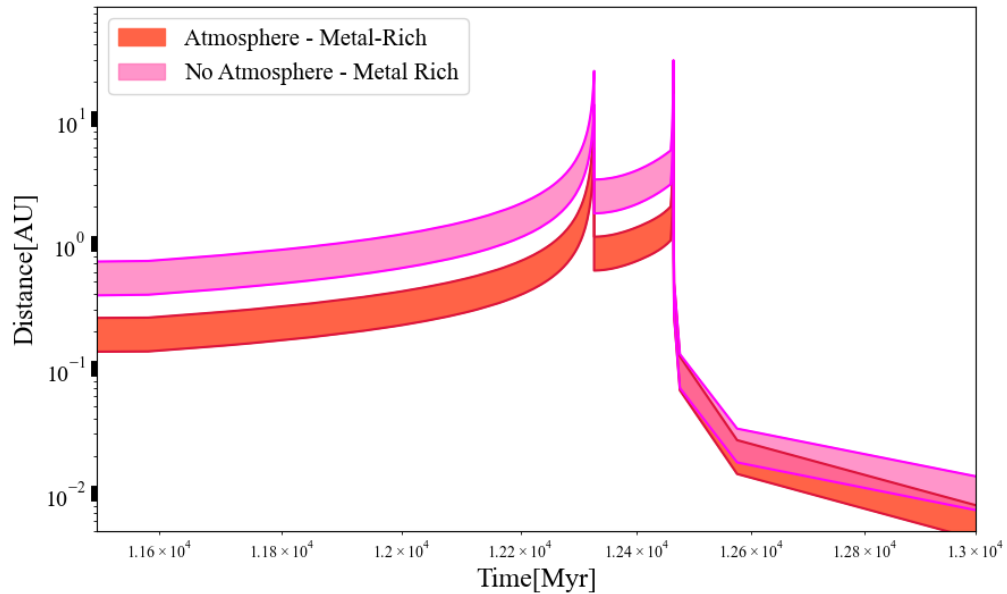


Figure 2.12: This plot illustrates the alteration in the habitable zone for a metal-rich-covered surface, emphasizing the impact of a reflecting atmosphere. The comparison is made between scenarios with and without atmosphere, showcasing how atmospheric factors distinctly affect the extent of the habitable zone around the star.

As we all know, the atmosphere of a planet does not only reflect a part of the incoming radiation, it can also cause an increase in the temperature of the planet through the greenhouse effect. This effect is actually the reason why life is possible on Earth. Without the greenhouse effect caused by Earth's atmosphere, the temperature of the Earth would be too small to permit the existence of liquid water.

Ignoring the greenhouse effect is the most serious flaw of the calculations presented in this work. We will briefly discuss the possible impact of the greenhouse effect in what follows.

# Chapter 3

## Discussions

We have calculated the location of the habitable zone throughout the evolution of the planet's host star. We have studied the effect of different albedos, evolutionary codes, and assumptions on the spectral energy distribution of the central star. However, there are still important factors that we have not considered and that will need to be incorporated in the future. Most importantly, we have almost completely ignored the impact of a planet's atmosphere on its temperature, for example, the Greenhouse effect. The greenhouse effect describes the overheating that occurs in the atmosphere due to the absorption of thermal emission of the planet by certain molecules, for example, water vapor and CO<sub>2</sub>, in its atmosphere.

It is important to note, that heating through the greenhouse effect does not necessarily rely on the radiation received by the planet from the star. Tidal heating of planets close to the star may also lead to a significant increase in temperature. For white dwarfs, the different heating mechanisms including greenhouse effects have been estimated in [Barnes and Heller \(2013\)](#). Using cooling models for White Dwarf from 6000K to 4000K, ([Kozakis et al., 2018](#)) found that white dwarfs offer a tough environment for life as we know it and produce the Runaway Greenhouse effect that evaporates water. Another study ([Barnes and Heller, 2013](#)) found that it is almost impossible for life to exist around White Dwarfs and Brown Dwarfs due to water evaporation in previous phases. Notwithstanding, there's perhaps a chance that the planets around a white dwarf turn habitable again.

In any case, the increased high-energy radiation during the white dwarf stages can generate a variety of effects that are important for generating and maintaining life. Evaporation of the atmosphere through high energy EUV photons produced by the white dwarf in the proximity of the planet might further complicate the impact of an atmosphere on the habitable zone around white dwarfs. It is even possible that evaporation completely eliminates the atmosphere ([Schreiber et al., 2019](#)). Furthermore, as we commonly know, UV radiation is poisonous for skin cells leading to burns and even cancer. On the other hand, and contrary to prevailing notions of UV radiation's

detrimental effects on life, these UV photons are also essential for the creation of life. The amount of energy from these rays can help to produce derivatives such as nucleobase uracil and pyrimidines in ice molecules.

From observational studies, very few planets have so far been detected around white dwarfs. These few planets, however, cover distances from 0.07[AU] to 2500[AU] ([Veras, 2021](#)). Planets close to the white dwarf are usually assumed to reach this location through instabilities in planetary systems ([Debes and Sigurdsson, 2002](#)).

Independent of all these details that would need to be incorporated to properly estimate the location of the habitable zone, it is important to note that we did not estimate the evolution of the location of a planet around an evolving star. This evolution is very different from the evolution of the habitable zone. The main processes that affect the location of a planet are mass loss from the star and tidal friction. When the Sun evolves into a giant, planets currently in the habitable zone will most likely fall into the Sun. The evolution of the location of a planet when the star evolves has been calculated, for example, in ([Ronco et al., 2020](#)). In [Figure 3.1](#) we show the distance of a Jupyter-like and Neptune-like planet to the star when the latter evolves into a giant for different initial separations.

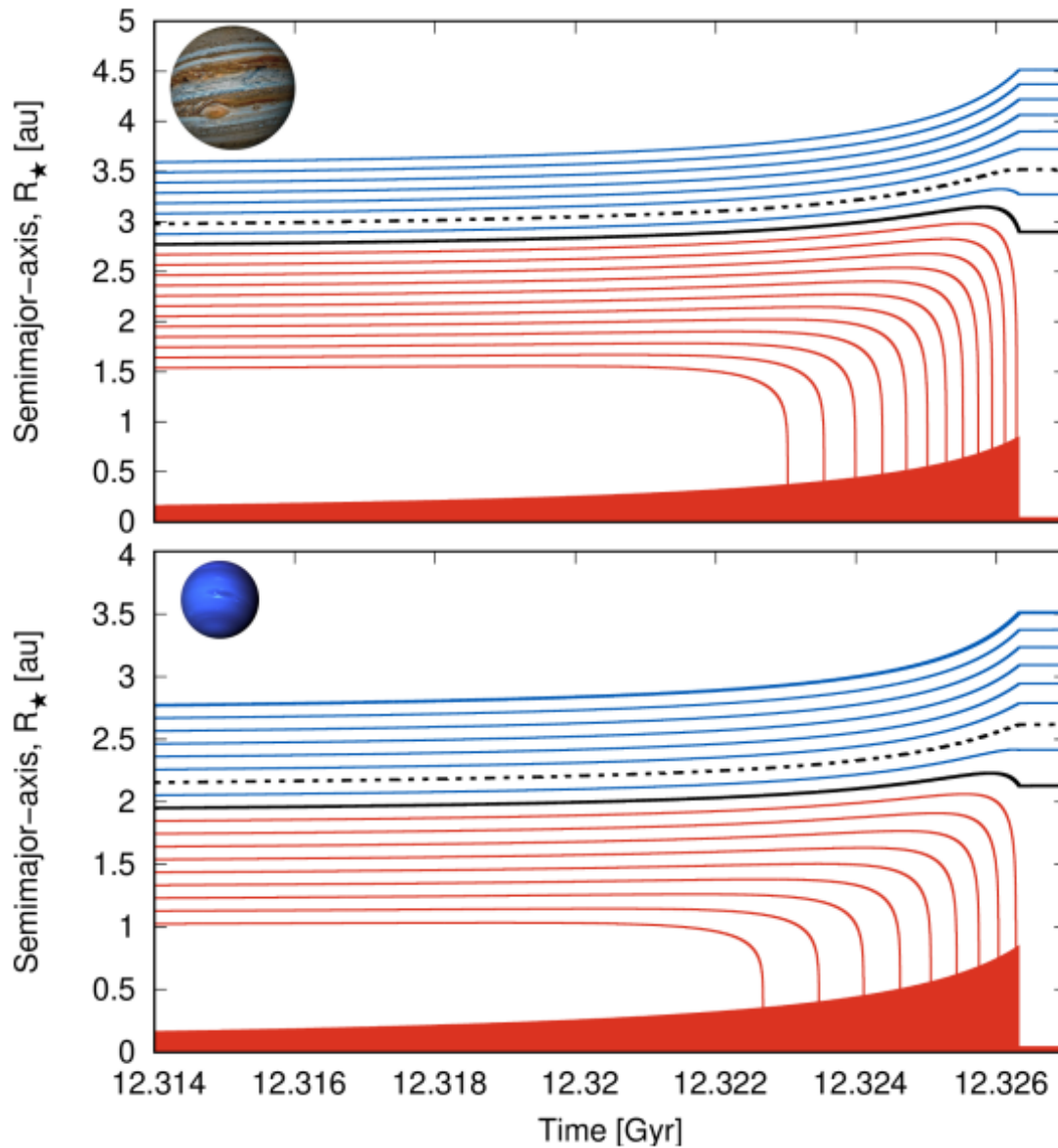


Figure 3.1: This plot visualizes the evolution of a Jupyter-mass and Neptune-mass planet depending on their initial distance. The red lines indicate the distance at which the planet would fall into the star, and the blue lines indicate the planet would be ejected. The red-filled area represents the radius of the host star. From [Ronco et al. \(2020\)](#).

# Chapter 4

## Conclusions

What can we get from all of this? Our hypothesis started from the evolution of a star. If the luminosity, radius, and temperature change, the habitable zone will change too. From the equilibrium temperature of the planet, we estimated the distance of the habitable zone from the star and started simulating with SSE.

Our result was that the habitable zone is eventually getting closer or farther depending on the evolution stage. Nevertheless, it must be considered more parameters that involve planet characteristics, such as the albedo.

The percentage of energy reflected by the surface changes the location of the habitable zone because it affects the warming of the planet. A planet that absorbs most of light is going to displace its habitable zone further than a planet that reflects most of the light. Furthermore, the albedo changes depending on the material. We test the difference between a constant albedo with a snow surface and a metal-rich surface.

To test the accuracy of our model, we incorporated realistic white dwarf spectra and calculated the evolution of the habitable zone, and the result is compared to our models. There are some minor changes caused by the fact that the spectral energy distribution of white dwarfs don't fit exactly as black bodies. Finally, we compared the evolution of the habitable zone using different stellar evolution codes, that is SSE and MESA. The latter is more accurate and includes complicated phases such as the thermal pulses on the AGB, but broadly speaking SSE is enough to understand the evolution of the habitable zone.

Last but not least, for a more accurate determination of the habitable zone additional processes such as the greenhouse effect, other soils, tectonic plates, atmosphere evaporation, and UV radiation (which may play a vital role in the formation of life in the Abiogenesis zone) need to be taken into account.

I thought of the distant future and the things we'd have, and discounted my wildest guesses as inadequate. Immortality? Achieved in the nineteenth millennium X. R. and discarded in the twenty-third because it was no longer necessary. Reverse entropy to rewind the universe? Obsolete with the discovery of nolanism and the concurrent cognate in the quadrate decal. Sounds wild? How would the word quantum or the concept of a matter-energy transformation sound to a Neanderthaler? We're Neanderthalers, to our descendants of a hundred thousand years from now. You'll sell them short to make the wildest guess as to what they'll do and what they'll be.

The stars? Hell, yes. They'll have the stars.

*The Lights In The Sky Are Stars*

**Fredrick Brown, 1953**

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