Stellar Evolution and Effects of Variable Composition on Habitable Systems

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Introduction

Habitable Zones have traditionally been defined as the location around a star where liquid water could exist on the surface of an orbiting planet.

We know that as stars age, this region moves away from the star due to the gradual increase in temperature and luminosity. Therefore, any orbiting planets may only have a relatively short time in which they might remain habitable.

We want to study how different stellar parameters, like mass and composition, affect the lifetimes of habitable planetary systems. In particular, we've found that even just varying the oxygen abundance within a star can significantly alter stellar evolution and thus habitable zone distances and lifetimes.

Ultimately, we'd like to learn what kind of star could potentially host a planet that remains in a continuously habitable zone for at least 2 Gyr – this is very approximately the amount of time it took for life on Earth to change the atmospheric composition sufficiently that it would be detectable from another star with the kind of missions recommended in the most recent Decadal Review of Astronomy and Astrophysics. This may help narrow down the search for Earth-like planets in the future.

Methods

Using the TYCHO simulator, we have modeled the stellar evolution for 152 sun-like stars (all F, G, K-types) all with differing combinations of mass and composition.

TYCHO outputs information for each time-step of a star's evolution to a file (which can be used to plot an HR-diagram, among other things). This helps us determine an acceptable estimate on the Zero Age Main Sequence (ZAMS) and allows us to study the general behavior of the star until it leaves the main sequence (Terminal Age Main Sequence, TAMS).

It is important to understand how long a star remains on the MS because it is the most stable and long-lasting period during the star's lifetime.

To calculate the Habitable Zone distances around each different star at each point in its evolution, we used the equations from Kopparapu et al. 2013, combined with our TYCHO output files, to estimate changes in HZ distances with time.

The aforementioned group derived these equations using radiative and convective planetary atmosphere models and synthetic stellar spectra inputs (produced by PHOENIX simulator). They parameterized the predicted distance from a star for the inner and outer edges of the habitable zone, as a function of stellar temperature and luminosity, for several kinds of planetary atmospheres.

We then were able to write a Fortran program that reads in the TYCHO output file, and simultaneously performs an operation to calculate these inner and outer HZ boundaries for both the optimistic (Recent Venus to Early Mars) and conservative (Runaway Greenhouse to Maximum Greenhouse) cases presented in the paper.

Finally, we input the columns of data into IDL and plot.

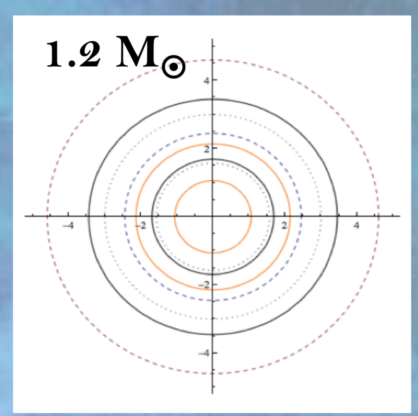
One of our first tasks was to define the parameter space for all 152 models. There were four models for varying Oxygen abundances, (2 enriched cases, and 2 depleted cases, relative to standard and with a fixed Z, this reflects variations observed in nearby stars) and metallicity variations from 0.1 to 1.5 solar value, modeled at each tenth.

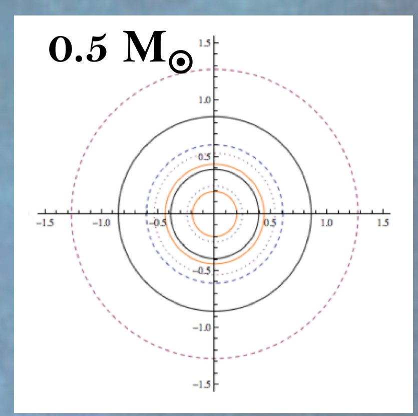
	Stellar Mass							
Composition	0.5 M⊙	0.6 M⊙	0.7 M⊙	0.8 M⊙	0.9 M⊙	1.0 M⊙	1.1 M⊙	1.2 M⊙
1.0 Z⊙	5A	6A	7A	8A	9A	0A	1A	2A
1.48 (O+)	5B	6B	7B	8B	9B	0B	1B	2B
2.28 (O ++)	5C	6C	7C	8C	9C	0C	1C	2C
0.67 (O-)	5D	6D	7D	8D	9D	0D	1D	2D
0.44 (O--)	5E	6E	7E	8E	9E	0E	1E	2E
1.5 Z⊙	5F	6F	7F	8F	9F	0F	1F	2F
0.1 Z⊙	5G	6G	7G	8G	9G	0G	1G	2G
0.2 Z⊙	5H	6H	7H	8H	9H	0H	1H	2H
0.3 Z⊙	5I	6I	7I	8I	9I	0I	1I	2I
0.4 Z⊙	5J	6J	7J	8J	9J	0J	1J	2J
0.5 Z⊙	5K	6K	7K	8K	9K	0K	1K	2K
0.6 Z⊙	5L	6L	7L	8L	9L	0L	1L	2L
0.7 Z⊙	5M	6M	7M	8M	9M	0M	1M	2M
0.8 Z⊙	5N	6N	7N	8N	9N	0N	1N	2N
0.9 Z⊙	5O	6O	7O	8O	9O	0O	1O	2O
1.1 Z⊙	5Q	6Q	7Q	8Q	9Q	0Q	1Q	2Q
1.2 Z⊙	5R	6R	7R	8R	9R	0R	1R	2R
1.3 Z⊙	5S	6S	7S	8S	9S	0S	1S	2S
1.4 Z⊙	5T	6T	7T	8T	9T	0T	1T	2T

Results

We needed to distinguish between overall metallicity of a star and varying a single abundance of one element. The metallicity of a star describes the proportion of matter in star other than Hydrogen and Helium. When we scale metallicity (Z) we do it relative to the sun's metallicity.

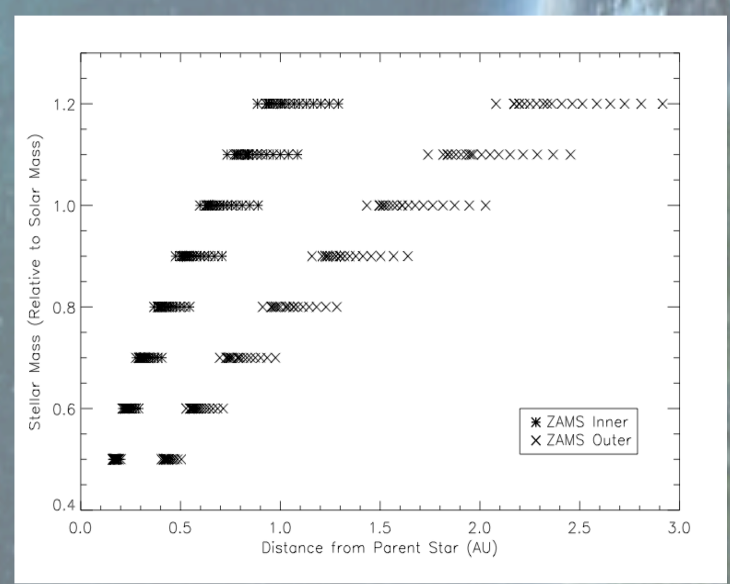
Our early models (Mathematica) are plotted to resemble the physical boundaries of the Habitable Zone around a star (axis = AU). These figures show how the HZ can vary widely between different types of stars.



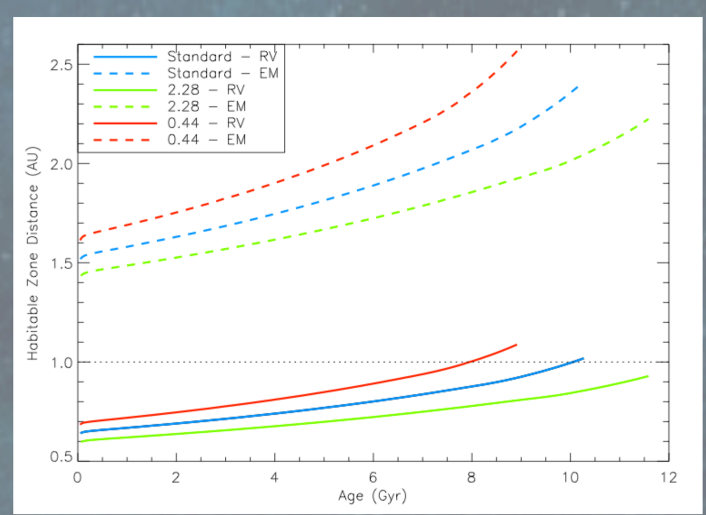


For both figures, the dotted lines are for 0.1 $Z_{\odot}$ at the beginning of the MS, the dashed lines are for 0.1 $Z_{\odot}$ at the end of the MS – blue to pink shows the range of HZ from beginning to end. The orange lines are for 2.28 [O] (double enriched oxygen) at ZAMS, black lines for 2.28 [O] at TAMS, exhibiting the evolving range of the HZ.

We initially wanted to see how all 152 stellar evolution models plotted out together, to examine any general trends that appear. This figure shows all cases (ZAMS). With increasing mass, it is interesting to note that there is both a widening of the overall HZ range, as well as a larger spread in the HZ distances due to compositional variation.

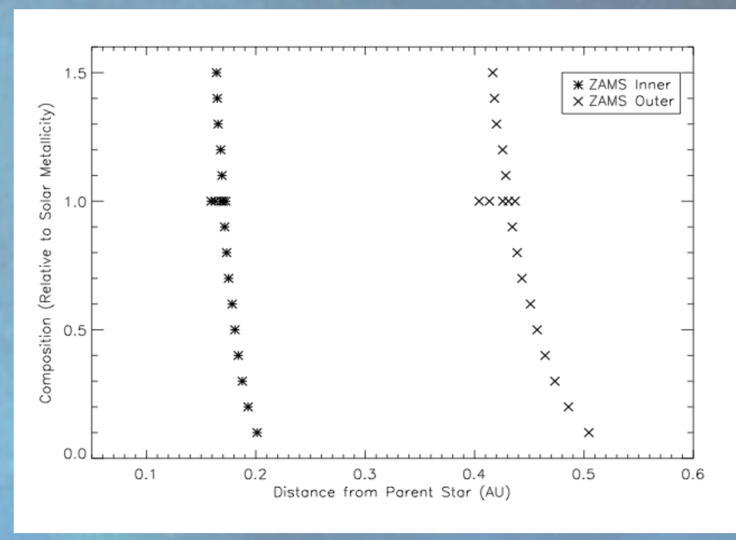


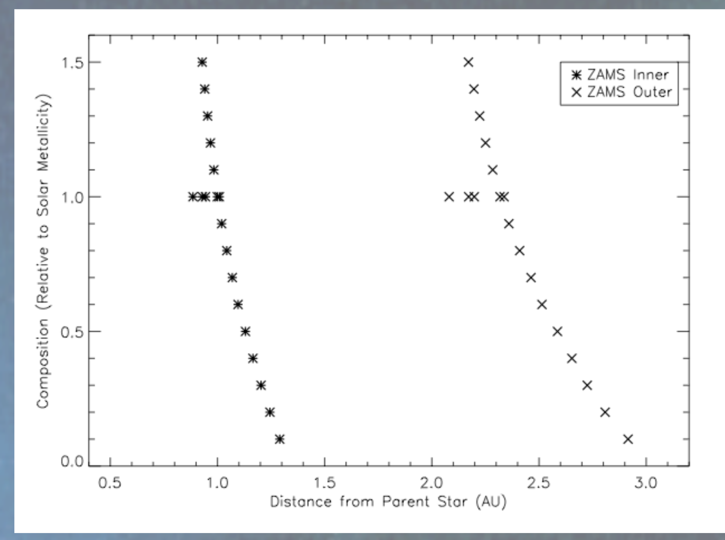
Another one of our goals was to quantify how much the distance AND lifetime of the Habitable Zone can change depending on stellar composition. Here we demonstrate that changing oxygen alone can affect the lifetime of a star (and the HZ). With more oxygen, it will be closer to the star than it would be to a star with less oxygen.

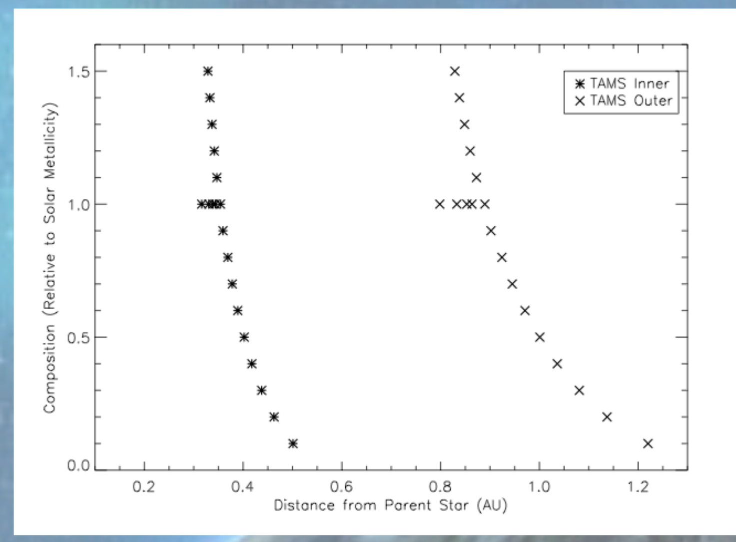


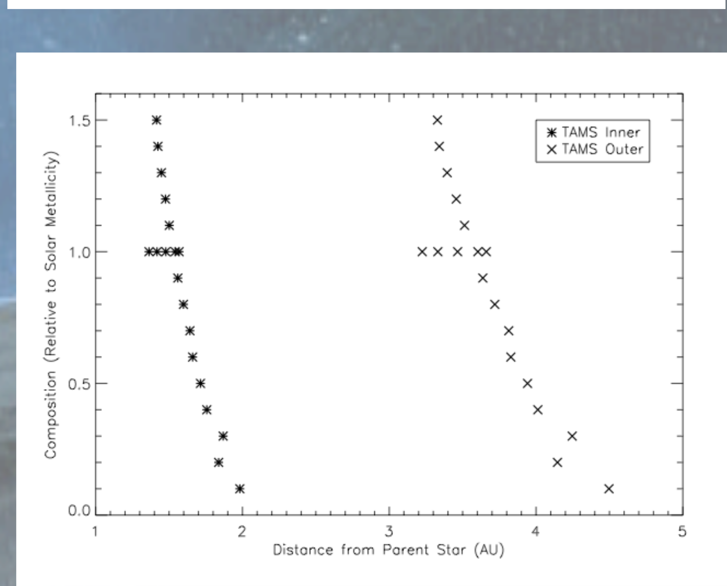
1 AU line plotted for reference (Earth's distance to Sun)

We have examined how changing the oxygen alone compares to scaling the entire metallicity of a star. For both star types, we see the same increase in HZ distance with decreased metallicity.





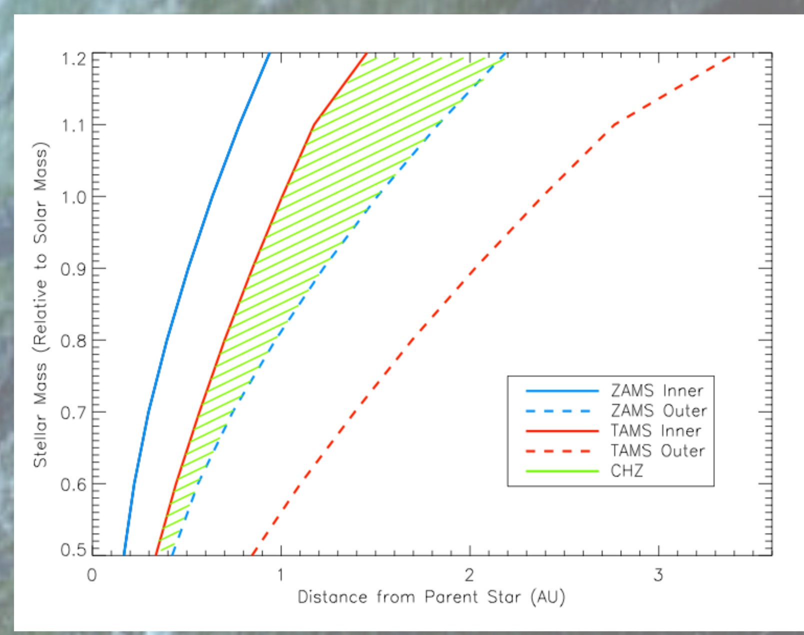


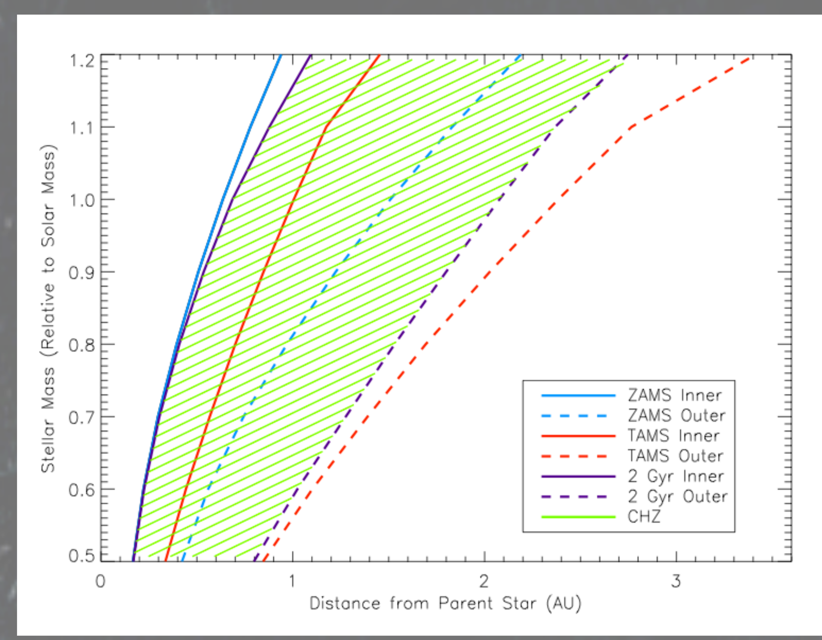


Figures show 0.5 M⊙

Figures show 1.2 M⊙

These figures explicitly reveal how dependent the HZ distance can be on the host star's composition, and that even changing one element can have a noticeable effect on HZ distances. Notice how the ranges differ somewhat between ZAMS and TAMS, and the more massive star has a much larger evolving HZ.





Finally, we wanted to quantify how long each kind of star might maintain a HZ for any orbiting planets. These figures (for solar-type) represent the "Continuously Habitable Zone" where a planet at the right distance could remain in the "goldilocks zone" for the entire MS lifetime of the star. The first figure shows just the overlap between the ZAMS – TAMS distances. However, we need to define the CHZ more carefully. The second figure shows the CHZ for the first 2 Gyr after the beginning of the MS until the 2 Gyr before the TAMS. This gives us a better idea of the real opportunity that might exist for planets to remain habitable for a long time.

Conclusions

Overall, we find that it is extremely important to consider what the host star is made of when we want to determine the habitability of any planetary system. Changing just one element can have significant effects on stellar evolution, so it is not enough to simply consider the overall metallicity of a star. We also must be careful in quantifying our HZ lifetime, because it varies widely among different-mass stars.

References

Kopparapu et al. 2013. "Habitable Zones Around Main Sequence Stars: New Estimates"

Young et al. 2012. "The Impact of Stellar Abundance Variations on Stellar Habitable Zone Evolution"