**ChromaStar Lab 2: Exo-planet life zone around main sequence stars**

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**Level:** High School to second year University

**Purpose:** To experimentally investigate the dependence of the planetary habitable zone (or life zone) on the effective temperature (*T*eff) of main sequence (MS) host stars. To explore the role that albedo and the greenhouse effect have on the life zone. To confirm the possibility for methane-based life on Titan.

**Background:** We assume that life requires chemical reactions that must take place in a liquid *solvent* such as water on the planet’s surface. The *circumstellar habitable zone* (or life zone, also called the “Goldilocks zone”), is the range of distances that a planet must have from its host star, or, equivalently, the radius that its circular orbit around the host star must have, for the surface temperature on the planet, *T*Surf, to be in the right range for life-bearing chemistry to be possible.

The life zone defines a ring centered on the host star that is bounded by two circles that can be calculated for any star-planet system: The *steam line*, with distance *d*steam from the center of the host star, and the *ice line*, with distance *d*ice from the host star. If the star’s orbit lies within *d*steam from the host star, then the *T*Surf value is above the boiling point for the solvent, *T*boil, and the solvent will be in the form of vapour in the planet’s atmosphere, or, if the *T*Surf value is high enough, the solvent particles will have escaped into space. If the star’s orbit lies beyond *d*ice from the host star, the planet’s *T*Surf value is below the freezing point for the solvent, *T*freeze, and the solvent will be in solid form.

A planet’s “*albedo*”, *A*, ( Latin for “whiteness”) is the fraction of the host star’s incident light (the *irradiance*) that is reflected from the planet’s surface *instead* of being absorbed by the planet – this fraction of the incident light does *not* contribute to the heating of the planet. The value of *A* might depend, among other things, on the fraction of the planet’s surface covered by light colored material such as deserts and glaciers, or the fraction covered on average by light colored cloud decks in the planet’s atmosphere. The value of *A* must range from 0 to 1, has no units, and for Earth the value is about 0.3.

A planet’s atmospheric *greenhouse* *effect*, *ΔT*, “delta *T*”, in K, can be modeled simply as an offset to the value of *T*Surf that the planet would otherwise have if there were no atmosphere. It accounts for the insulating effect the atmosphere can have if it blocks some of the heat trying to escape from the planet. The value of *ΔT* can be set to *negative* values (*ΔT < 0*), in which case it becomes an “*icehouse*” effect – this might arise if the most important role played by the atmosphere is to *block* starlight from reaching the planet’s surface.

For a given host star, the values of *d*steam and *d*ice (*ie.* the location of the life zone), will also depend on the *planet’s* parameters as set in the second panel (labeled “Planet”) of the ChromaStar input, which includes the values of the planet’s atmospheric greenhouse effect, *ΔT*, and its surface reflectivity (or “albedo”), *A*. The value of *T*freeze will depend on the choice of solvent (it does not have to be water!), and the value of *T*boil will depend on both the choice of solvent and the *planet’s* atmospheric *surface* pressure, *P*Planet.

Note that in this demonstration we will only be investigating the life zone for relatively cool main sequence (MS, luminosity class V) stars. For life to have a chance of arising, we expect that the host star has to be one that will be stable for billions of years, and has not recently undergone any changes that significantly change the conditions on surrounding planets.

**Optional:** The *T*Surf value of the *planet* depends on the balance between the rate at which the planet is being *heated* by illumination, or *irradiance*, from the host star, and the rate at which the planet is being cooled by emitting its *own* thermal, or blackbody, radiation (see ChromaStar Lab 1 on the *T*eff-Color relation). Note that for a planet of around Earth’s *T*Surf value, 295 K, the spectrum of the emitted blackbody radiation has its maximum brightness at a wavelength, *λ*Max, in the infrared (IR) band, and is invisible to the unaided eye. The planet naturally has whatever *T*Surf value is needed to balance the heating and cooling rates, and this leads to the following equation for *T*Surf:

*(T*Surf *– ΔT)4 = L*bol *(1-A) / (16πσd2)*

Where *L*bolis the host star’s bolometric luminosity in Watts (W), *d* is the distance of the exo-planet from the center of its host star in m, *A* is the albedo (ranging from *0* to *1*), *ΔT* is the planet’s atmospheric *greenhouse effect*, in Kelvins (K), and *σ* is the Stefan-Boltzmann constant of blackbody radiation – a physical constant. Note that this is an equation for *(T*Surf *– ΔT)4* – we must take the fourth root of the value of the right-hand-side (RHS), then add the greenhouse effect, *ΔT*, to find the value of *T*Surf. Note that the planet’s radius, *R*Planet, does not appear in Equation (1) – the cooling and heating rates both depend on *R*Planet*2*, so it cancels out.

Re-arranging, we can solve for the distance that corresponds to a given *T*Surf value

*d2 = L*bol *(1-A) / {16πσ (T*Surf *–ΔT)4 }* (1)

Note that we must take the square root of the RHS to find *d*. By setting the value of *T*Surfin Equation (1) to the value for *T*boil, and then to the value for *T*freeze, we can calculate the values of *d*steam and then *d*ice, and, hence, determine the life zone.

The value of *L*bolfor the host star will depend on its stellar parameters as set in the top panel (labeled ”Stellar”) of the ChromaStar input: The star’s effective surface temperature, *T*eff, its logarithmic surface gravity, log *g*, and its mass, *M*.

**Apparatus:**

The ChromaStar stellar atmospheric modelling WWW application: ([www.ap.smu.ca/OpenStars/](http://www.ap.smu.ca/~ishort/OpenStars/GrayStar3/GrayStarV4.html) )

Make sure you are starting with a fresh ‘reload’ of ChromaStar so that all the input parameters have their default values (among other things, the *stellar* parameters will default to solar values and the *planetary* parameters will default to Earth’s values - if you think that some values are not reverting to default, try clearing your browser’s history with all optional data types checked, and ‘reload’ again).

Load *three* different instances of ChromaStar in three different browser tabs so that you can perform *blink comparisons* of models with different parameters. This is a valuable technique for comparing and contrasting models that differ from one another in a controlled way.

A spreadsheet application: (OpenOffice Calc (free!), MS Excel, …). You must be able to ‘Save’, ‘Export’, or ‘Print’ the file in a platform-independent format such as PDF – you might have to submit it electronically.

**Initial set-up:**

Find the *Life Zone* panel in the ChromaStar output. The scaling of this image in the radial direction outward from the center of the host star is *logarithmic*, so the size of the stellar image is exaggerated with respect to the location and width of the life zone depiction. Note that the distances from the center of the host star to the steam line (red circle) and the ice line (blue circle) are indicated in Astronomical Units of distance (AU), and that the boiling point of the solvent currently selected, *T*boil, is displayed in K. There is also a black circle, not visible with the default model, indicating the location of 1 AU from the center – by *definition* the Earth’s average distance from the center of the Sun.

**Procedure:**

1. Set up a sequence of three main sequence (MS) stars. In the *first* browser tab, turn the *T*eff up to 7200 K (a spectral class F0 V star), turn the log*(g)* value down to 4.4, and the *M* value up to 1.5 MSun. (There is a relationship among these three quantities that defines the MS.)

Leave the *second* tab on its default model – the Sun.

In the *third* tab, turn the *T*eff down to 3800 K (a spectral class M0 V star), turn the log*(g)* value up to 4.6, and the *M* value down to 0.5 MSun.

*Confirm* that all three of these models are approximately centered on the MS (class “V”) in the HRD.

*Note and record* the bolometric luminosity, *L*Bol, of each model.

1. Adjust the zoom factor and the horizontal and vertical scrolling so that the entire *Life Zone* panel is visible and aligned among all three tabs. Blink the tabs against each other in sequence from hottest to coolest. Note that the diagram of the life zone gets automatically re-scaled to fit in the panel for each model, but the black circle is an important reference line – it is always 1 AU from the center of the star. How does the location of the life zone (values of both *d*steam and *d*ice) depend on the *T*eff value of MS star host? Is this what you would expect? – It might help to think about the values of *L*Bol?
2. How does the *width* of the life zone (*d*ice - *d*steam) depend on the *T*eff value of MS star host?
3. Click ‘Reload’ on all three browser tabs so that all three are modeling the Sun (*confirm* that this is the case!).
4. In the “Planet” tab, the default value of the albedo, *A*, should be about 0.3. In the *first* tab turn the albedo down to 0 (*all* sunlight absorbed, *none* reflected), and in the *third* tab set the value of *A* to 0.95 (5% of sunlight absorbed, 95% reflected). Line up the three *Life Zone* panels and blink them against each other. How do *d*steam and *d*ice depend on the value of *A* for a given host star? Is this what you would expect?
5. **Optional activity 1:** The Cassini mission to the Saturn systemdiscovered lakes of *liquid* methane (H4C) on the surface of the major moon Titan – *ie.* that Titan is in its *liquid methane* life zone! Organic chemists think liquid methane might be a viable solvent for life-bearing chemistry. Look up the “planetary” parameters, *ΔT*, *P*Surf, and *A*, for Titan, and make sure “Methane” is selected for the solvent. Can you confirm that Titan is in the liquid methane life zone? You’ll need to know the distance of the Saturn system from the Sun in AU.
6. **Optional activity 2:** Some people have suggested that we can address the problem of climate change be deploying floating platforms on the ocean with sky-high nozzles that would spray fine droplets of ocean water into the upper atmosphere. These droplets would be reflective, and would increase Earth’s *A* value – this approach is an example of *planetary engineering*. If the greenhouse effect, *ΔT* were to increase by 5 K from its default value, by how much would *A* have to change from its default value to maintain our current values of *d*steam and *d*ice?

**Analysis & Discussion:**

1. **Challenge question:** In Step 5 of the *Procedure* we could only turn the value of A up to 0.95, but not all the way to a value of 1.0. Why not? Referring to Equation (1) will help.