Stellar System Creator

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CONTENTS

CHAPTER ONE

INTRODUCTION

The Solar System Creator is a python package that aims to ease the creation of realistic stellar systems in sci-fi settings. With minimal input, the user is able to create stars, planets, moons, asteroid regions and other celestial bodies, with accurate physical characteristics, declare their habitability, extract physical characteristics and visualize them.

CHAPTER

TWO

QUANTITIES

Here, we will explore the various physical quantities found in this package.

2.1 Material

2.1.1 Mass

Mass is the quantity of mater in a physical body. In the context of this package, mass determines most of other physical characteristics, like *radius*, *luminosity*, *spin period* and *lifetime*.

Suggested (approximate) masses:

1. For moon-like satellites, less than 0.05 earth masses (Me)
2. For rocky planets: up to around 5 earth masses
3. For ice-giants: between 5 and 100 earth masses
4. For gas-giants: between 100 earth masses and 10 jupiter masses (Mj)
5. For long-lived, red stars: 0.081 and 0.5 solar masses (Ms)
6. For habitable stars: 0.6 to 1.4 solar masses
7. For short-live, big blue stars: 1.4 to 50 solar masses.

2.1.2 Density

Density ($\rho = \frac{M}{V}$) is the *mass* per unit *volume* of an a substance (or celestial object). Usual densities in the solar system are between 0.5 and 7 grams/cm^3.

2.1.3 Composition Type

The composition type of planets, planetoids, asteroids etc. is what the approximate composition of a celestial object will be. There are two types of iron worlds, two types of rocky worlds, four types of water worlds, one type of ice- and one of gas-giants.

Even though the composition is not accurate by itself, I find that the *density* and *radius* of asteroids and moons that are not rocky, can be generally approximated by the four different water worlds. Same for small gassy worlds (like Pluto).

2.1.4 Chemical Composition

Chemical composition is the ratio of different chemical compounds that constitute a substance. There are 3 main substances that are portraited in this package. That does not mean that there can not be other, it is just what the planetary *radius* models represent.

The main chemical compounds are iron (Fe), rock (MgSiO3), water (H2O), helium (He), Hydrogen (H2) and methane (CH4).

2.2 Geometric

2.2.1 Radius

Radius is the variable that defines the size of celestial objects. The radius determines the *circumference*, *surface area*, *volume* and *density*. among other characteristics. The suggested radius is determined by the *mass* of the object via various radius models. Use values ± 8 % around the suggested value.

Models used:

1. For planetary models, see https://arxiv.org/pdf/0707.2895.pdf.
2. For hot gas-giant models, see https://arxiv.org/pdf/1804.03075.pdf.
3. For star models, see https://academic.oup.com/mnras/article/479/4/5491/5056185.

2.2.2 Circumference

The circumference is determined by the radius $C = 2\pi r$.

2.2.3 Surface Area

The surface area is determined by the radius $A = 4\pi r^2$.

2.2.4 Volume

The volume is determined by the radius $V = \frac{4\pi}{3} r^3$.

2.3 Rotational

2.3.1 Spin Period

The spin period is the amount of time it takes for a celestial body to rotate around itself compared to the distant stars.

Planetary spin period is determined by the *mass* and *radius* of the celestial body. The more massive the body, the faster it rotates. If there are satellites around the planet large enough (e.g. earth-moon), there is a substantial transfer of angular momentum between the two bodies, making the planet slow down (earth spin period would have been around 16 hr).

2.3.2 Day Period

The day period of a child body is determined by the *spin period* and the *orbital period* around the parent body.

2.3.3 Axial Tilt

The axial tilt of a child body, also known as obliquity, is the angle between an object's rotational axis and its orbital axis.

As of now, it is cosmetic and does not determine any other characteristics.

2.4 Life

2.4.1 Age

The suggested age of a star is set to be half of its *lifetime*. The suggested age of any other object is determined by it's parent age.

2.4.2 Lifetime

The lifetime of stars is determined by its mass and its luminosity ($T = \frac{M}{L} \cdot 10$ billion years).

The lifetime of each other body is determined by the lifetime of the parent minus a hundred million years, which is roughly the amount of time it takes for planets to form around stars (or satellites to be captured). It is by no means binding.

2.5 Surface

2.5.1 Emission

Albedo

(Bond) albedo A is the measure of reflection of incident radiation of an object. A value of $A = 0$ means the object absorbs all incident radiation. A value of $A = 1$ means the object reflects all incident radiation.

Albedo values for planets in our solar system:

1. Mercury, Mars ~0.14.
2. Earth, Uranus, Neptune ~ 0.3.
3. Jupiter, Saturn ~ 0.5.
4. Venus ~ 0.75.

More information and example values on: https://en.wikipedia.org/wiki/Albedo.

Emissivity

Emissivity ϵ is the measure of how much of the overall radiation on the surface of an object is emitted outside. Most planets have an emissivity close to 1 (the maximum value). Emissivity of 0 (minimum value) means that no radiation is emitted.

Heat Distribution

Heat distribution β is the measure of how well a planet distributes heat, and can take values from 0 to 1. It highly depends on the rotation speed of the planet.

The faster the rotation, the closer the number is to 1 (usually 1 for all non-tidally locked planets). The heat distribution is 0.5 for a planet that is *tidally locked* to its parent.

Normalized Greenhouse

The normalized greenhouse effect g is a measure of the greenhouse effect in the atmosphere of a planet. It takes values between 0 and 1. The closer to 1, the higher the temperature of the planet will be. When you get close to 1 (e.g. 0.99), adding a new 9 at the end (e.g. 0.999) will dramatically increase the effect.

The normalized greenhouse effect on earth is approximately 0.34.

Incident Flux

Incident flux is the incoming radiation flux from all major sources. The total incident flux is added from the parent, the parent of the parent etc.

The incident flux S from a single source of *luminosity* L at effective distance :math:'r_{rm eff}' is given by the equation: $\frac{L}{r_{\rm eff}^2}$.

For a child orbiting at *mean distance* a and *eccentricity* e, there are two types of effective distance we care about. The first is the one that is related to the average incoming flux and is given by: $r_F = a\left(1-e^2\right)^{1/4}$.

The second is the one that is related to the average surface temperature and is given by: $r_T \approx a(1+\frac{1}{8}e^2+\frac{21}{512}e^4)$.

For more information: https://arxiv.org/pdf/1702.07314.pdf (eq. 3, 17, 19).

Temperature

The surface temperature of an object can be defined differently for objects that produce significant radiation (stars) and ones that are mostly heated by another stellar body (planets, satellites).

For a star of *luminosity* L in solar luminosities and *radius* R in solar radii, the surface temperature is given by the ideal body equation: $\frac{L}{R^2} \cdot 5778$ K.

For a planet of *bond albedo* A, *emissivity* ϵ, *heat distribution* β, *normalized greenhouse* g and *incident flux* S, the surface temperature is given by the equation: $\left(\frac{(1-A)S}{\beta\epsilon(1-g)}\right)^{1/4} \cdot 278.5$ K.

For more information of the planetary surface temperature: https://arxiv.org/pdf/1702.07314.pdf (eq. 6 and 16)

Luminosity

Luminosity is the measure of the emitted radiation from an object. It is determined by the *mass* of the object, and the *incident flux* if it is relatively higher than the emitted flux of radiation.

For star of *mass* M in the main sequence, the luminosity is given by various mass-luminosity relationships as in https://en.wikipedia.org/wiki/Mass-luminosity_relation. Use values ± 8 % around the suggested value.

For a planet of *surface temperature* T, *temperature-based incident flux* S_T, *albedo* A and *surface area* A_S, the luminosity is determined by: $\sigma A_S T^4 + A S_T A_S / 4$, where σ is the Stefan-Boltzmann constant.

For more information on planetary luminosity:

1. https://www.acs.org/content/acs/en/climatescience/atmosphericwarming/singlelayermodel.html
2. https://en.wikipedia.org/wiki/Planetary_equilibrium_temperature

Peak Wavelength

The *surface temperature* T of an object, if it is an (close to) ideal black body object can be associated with a profile of emitted wavelengths, with a single maximum. For our sun, the maximum of the emission spectrum is around 500 nm (green).

In general, the peak wavelength it is given by: $\lambda = \frac{2.898 \cdot 10^6 \,\mathrm{nm\,K}}{T}$.

2.5.2 Gravity

Surface Gravity

Escape Velocity

2.5.3 Internal Heating

Tectonic Activity

Primordial Heating

Radiogenic Heating

Tidal Heating

2.5.4 Induced Tide

2.5.5 Angular Diameter

2.6 Orbital

2.6.1 Eccentricity

Eccentricity e determines how elliptic the orbit of a child around a parent body is. $e = 0$ means that the orbit is circular, and $e = 1$ means that the orbit resembles a line (not a stable orbit).

The closer to $e = 0$, the more stable the orbit in single star systems.

For objects orbiting binary systems (P- or S-type), the preferred eccentricity is not zero.

2.6.2 Semi-Major Axis

Semi-major axis a is the mean distance between a child and a parent body.

2.6.3 Semi-Minor Axis

Semi-minor axis b is determined by the *semi-major axis* a and the *eccentricity* e: $b = a\sqrt{1-e^2}$.

2.6.4 Apoapsis

Apoapsis ($a(1+e)$) is the furthest distance between a child and a parent body. It is determined by the *semi-major axis* a and the *eccentricity* e.

2.6.5 Periapsis

Periapsis ($a(1-e)$) is the nearest distance between a child and a parent body. It is determined by the *semi-major axis* a and the *eccentricity* e.

2.6.6 Lagrange Position

Lagrange positions (L#) are (semi-)stable positions between two orbiting objects. Trojans are objects in the L4 and L5 positions, in front and behind the child object (denoted as +1 and -1 respectively) that is orbiting a parent object.

2.6.7 Contact

In this context, contact between two binary stars happens if the radius of at least one of the two stars resides outside the *Roche lobe* while the stars are in *periapsis*.

2.6.8 Roche Lobe

The Roche lobe is the region around a star in a binary system within which orbiting material is gravitationally bound to that star.

2.6.9 Orbital Period

Orbital period ($\sqrt{\frac{a^3}{M_{tot}}}$) is the time it takes for a child body to orbit around their parent. It is given by the *semi-major axis* a, and the total mass M_{tot} of child and parent objects.

2.6.10 Orbital Velocity

Orbital velocity ($\sqrt{\frac{M_{tot}}{a}}$) is the mean speed at which the child body travels around the parent body. It is given by the *semi-major axis* a, and the total mass M_{tot} of child and parent objects.

2.6.11 Orbit Type

Orbital type of a child object can be either prograde or retrograde - orbiting along or against the rotation of the parent.

2.6.12 Orbit Type Factor

Orbit type factor determines the *semi-major axis maximum limit*. It depends on the *orbit type* and is determined by the parent *eccentricity* e_p and the child *eccentricity* e_c.

1. For a prograde orbit, it is given by $0.4895(1 - 1.0305e_p - 0.2738e_c)$.
2. For a retrograde orbit, it is given by $0.9309(1 - 1.0764e_p - 0.9812e_c)$.

2.6.13 Orbital Stability

Orbital stability demonstrates if the orbit of the child object around the parent object does not exceed any limits. More specifically, for a stable orbit we must have:

1. *Periapsis* > *roche limit*.
2. *Semi-major axis* > *p-type critical orbit*.
3. *Apoapsis* < *semi-major axis maximum limit*.
4. Optional: *Semi-major axis* > *parent inner orbit limit*.
5. For rock worlds: *Semi-major axis* > *parent outer rock formation limit*.

2.6.14 Inclination

Orbital inclination is the tilt of a child object's orbit around a celestial body. It varies between 0 and 180. Between 0 and 90, the orbit is prograde. Between 90 and 180, the orbit is retrograde.

However, as of now, it is cosmetic and does not determine any other characteristics, including the *orbit type*.

2.6.15 Argument of Periapsis

Check out https://en.wikipedia.org/wiki/Argument_of_periapsis.

The argument of periapsis, as of now, it is cosmetic and does not determine any other characteristics.

2.6.16 Longitude of the Ascending Node

Check out https://en.wikipedia.org/wiki/Longitude_of_the_ascending_node.

The longitude of the ascending node, as of now, it is cosmetic and does not determine any other characteristics.

2.6.17 Semi-Major Axis Minimum Limit

The semi-major axis minimum limit is the *roche limit* of the parent for the specific child *density*, or the *p-type critical limit* in binary systems.

2.6.18 Semi-Major Axis Maximum Limit

The semi-major axis maximum limit is the *hill_sphere* multiplied by the *orbit type factor*.

2.7 Children Orbit Limits

2.7.1 Tidal Locking Radius

The tidal locking radius is the furthest distance a child would be tidally locked to its parent. Tidal locking means that an orbiting object around a parent turns around itself at the same amount of time it turns around its parent. One side of the planet is always faces the parent, while the other side does not.

The tidal locking radius is larger the more *massive* the parent is, and the more *old* it is. Many parameters of the child object determine the tidal locking radius, but they are hard to estimate, so treat this this number as a suggestion rather than a hard limit.

More info on:

1. https://en.wikipedia.org/wiki/Tidal_locking#Timescale,
2. https://physics.stackexchange.com/questions/12541/tidal-lock-radius-in-habitable-zones
3. https://www.sciencedirect.com/science/article/abs/pii/S0019103583710109 (eq. 10 in CGS units)

2.7.2 Roche Limit

Roche limit is the minimum distance d_{Roche} a child object of *mass* m, *radius* r and *density* ρ_m can orbit a parent object of *mass* M, *radius* R and *density* ρ_M before the child object breaks apart into pieces. An additional condition is that the child object must only be held together by its own gravity.

It is given the equation: $d_{Roche} = 2.44r\left(\frac{M}{m}\right)^{1/3}$ or $d_{Roche} = 2.44R\left(\frac{\rho_M}{\rho_m}\right)^{1/3}$.

2.7.3 Dense Roche Limit

Dense Roche limit is the *Roche limit* of a child of unknown *radius* and a parent object of *radius* R *density* 10 times bigger than the child *density*.

It is approximately: $5.2568R$.

2.7.4 P-type binary Critical Orbit

In close binary systems (p-type binaries) of two stars with *masses* m_1 and m_2 with $m_1 > m_2$, *mean distance* d and *eccentricity* e, the critical orbit limit is the *minimum* distance at which an orbit stays stable.

It is estimated by: $d(1.6 + 5.1e - 2.22e^2 + 4.12\mu - 5.09\mu^2 + 4.61e^2\mu^2 - 4.27e\mu)$, where $\mu = \frac{m_2}{m_1+m_2}$.

More info on: https://arxiv.org/pdf/2108.07815.pdf (eq. 3).

2.7.5 Inner Orbit Limit

The inner orbit limit of a parent for its children is the highest of *dense Roche limit* and *P-type critical orbit*. It is provided to assist the user determine the worst possible inner orbit limit.

2.7.6 Hill Sphere

Hill sphere is the maximum distance (r_H) an object (child) can affect even smaller body (grandchild), because of the presence of a bigger body around (parent). For example the moon is within the hill sphere of earth, and the hill sphere of earth is determined by earth's *mass* m *semi-major axis* a, and *eccentricity* e, and the sun's *mass* M.

It is given by the equation: $r_H = a(1-e)\left(\frac{m}{3M}\right)^{1/3}$.

If we looking at a single object that is part of a binary system, a more accurate determination of the Hill sphere is given by the *Roche lobe*.

2.7.7 Roche Lobe

Roche lobe (or sphere) (not to be confused with *Roche limit*) is the region around a star in a binary system within which orbiting material is gravitationally bound to that star.

For an object of *mass* m in a binary system, and a companion object of *mass* m_c, with a binary *mean distance* d and *eccentricity* e, the roche lobe is approximated by: $d(1-e)\frac{0.49\mu^{2/3}}{0.6\mu^{2/3}+\ln\left(1+\mu^{1/3}\right)}$, where $\mu = \frac{m}{m_c}$.

2.7.8 S-type binary Critical Orbit

In wide binary systems (S-type binaries) of two objects with *masses* m_1 and m_2 with $m_1 > m_2$, *mean distance* d and *eccentricity* e, the critical orbit limit is the *maximum* distance at which an orbit stays stable around a single object. This distance is different for each object and changes due to their mass difference.

For the primary star of *mass* m_1, μ is determined by the companions to the binary's mass ratio $\mu = \frac{m_2}{m_1+m_2}$.

For the secondary star of *mass* m_2, μ is determined by the companions to the binary's mass ratio $\mu = \frac{m_1}{m_1+m_2}$.

The critical distance is estimated by: $d(0.464 - 0.38\mu - 0.631e + 0.586\mu e + 0.15e^2 - 0.198\mu e^2)$.

More info on: https://arxiv.org/pdf/2108.07815.pdf (eq. 1).

2.7.9 Outer Orbit Limit

The outer orbit limit of a parent for its children is the lowest of *Hill Sphere* and *S-type critical orbit*. It is provided to assist the user determine the worst possible outer orbit limit.

2.7.10 Inner Rock Formation Limit

We use *Selsis insolation model* since it allows for easy, Solar system comparisons. Rock line is the distance at which iron and rock can form clusters, planetesimals and eventually planets. Since the rock line is determined by when rock and iron are more or less solid, I decided to use the boiling point of a fast rotating iron ball (*heating distribution* β 1, *albedo* A 0.15) @ $T = 2870$ K. for the optimistic inner rock line limit, giving a value of ≈ 0.087 A.U for our sun.

Distance estimation: $\left(\frac{T}{T_{\text{eff}}}\right)^2 \sqrt{\frac{1-A}{\beta}}$, with $T_{\text{eff}} = 278.5$ K (https://arxiv.org/pdf/1702.07314.pdf eq. 6 with $L = 1$).

2.7.11 Outer Rock Formation Limit

We use *Selsis insolation model* since it allows for easy, Solar system comparisons. Rock line is the distance at which iron and rock can form clusters, planetesimals and eventually planets. Since the rock line is determined by when rock and iron are more or less solid, I decided to use the melting point of a slow rotating (*tidally locked*) rock ball (*heating distribution* β 0.5, *albedo* A 0.85) @ $T = 600$ K to find the equivalent solar system distance and multiply by 5/3.1 (similar to the *early solar system water frost line*) (lowest temperature from http://hyperphysics.phy-astr.gsu.edu/hbase/Geophys/meltrock.html) for the optimistic outer rock line limit, giving a value of ≈ 0.281 A.U for our sun.

Distance estimation: $\frac{5}{3.1}\left(\frac{T}{T_{\text{eff}}}\right)^2 \sqrt{\frac{1-A}{\beta}}$, with $T_{\text{eff}} = 278.5$ K (https://arxiv.org/pdf/1702.07314.pdf eq. 6 with $L = 1$).

2.7.12 Inner Water Frost Limit

We use *Selsis insolation model* since it allows for easy, Solar system comparisons. As shown on the wikipedia page https://en.wikipedia.org/wiki/Frost_line_(astrophysics), there are different frost lines for different compounds. Water is important and seems to determine the line between gas planets and rocky planets.

It must be noted that gas giants can migrate to inner orbits after their creation, so it is not impossible to find one where venus or mercury would have been. It would however probably destabilize any other planets in its path.

The inner limit is taken from wiki's suggestion for big sized bodies at ~1.94 AU (~200 K).

2.7.13 Sol-Equivalent Water Frost Limit

We use *Selsis insolation model* since it allows for easy, Solar system comparisons. As shown on the wikipedia page https://en.wikipedia.org/wiki/Frost_line_(astrophysics), there are different frost lines for different compounds. Water is important and seems to determine the line between gas planets and rocky planets.

It must be noted that gas giants can migrate to inner orbits after their creation, so it is not impossible to find one where venus or mercury would have been. It would however probably destabilize any other planets in its path.

The Sol equivalent limit is from the average of the newest finds ~ 3.1 AU (~ 158.2 K).

2.7.14 Outer Water Frost Limit

We use *Selsis insolation model* since it allows for easy, Solar system comparisons. As shown on the wikipedia page https://en.wikipedia.org/wiki/Frost_line_(astrophysics), there are different frost lines for different compounds. Water is important and seems to determine the line between gas planets and rocky planets.

It must be noted that gas giants can migrate to inner orbits after their creation, so it is not impossible to find one where venus or mercury would have been. It would however probably destabilize any other planets in its path.

The outer limit is taken from wiki's mention on the early-days frost line at 5 AU (~124.5 K).

2.8 Insolation Models

2.8.1 Kopparapu

2.8.2 Selsis

2.9 Habitability

CHAPTER

THREE

INDICES AND TABLES

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