## 0.01 - Introduction

#### Introduction

So, you want to build a planet?

Good luck with that. See you around.

Had you going there, didn't I? 69

#### What This Is About

Writers, gamers, students, educators (fill in the blank) sometimes have need to create a planet. Oftentimes, they just rename Earth and get on with it (which is fine, don't get me wrong). But, if you want to tweak the settings (does this knob go all the way up to *eleven*?), you need some background and some tools and skills to help out.

That's what WorldCrafting101 is intended to be.

This is not an astrophysics course, or a cosmology seminar, or anything of the kind. I am a college history professor, aspiring writer, and science nerd from *way back*, who found that a lot of the more hands-on, DIY aspects of designing planets, moons, stars, etc. were either utterly lacking, assumed *way* too much prior knowledge, or required skills in maths that I don't possess and don't have time to acquire.

Sidebar: There is *no calculus here*. There's algebra (some of it a bit gnarly), some geometry, trigonometry, a *little* statistics, but all of it completely accessible to anyone with a basic education background. And, anyway, whenever I introduce an equation, I explain it fully, what all the variables are, where they come from, why they're there, and *how you figure out what values to put in them for your own work*.

## Say What? A Note About Terminology

There's a lot of terminology in this endeavor (*inertial frame*, *escape velocity*, *main sequence lifetime*, etc.), and -- I admit, I've invented some terminology myself for concepts or parameters that don't have an official one, or whose official name is more confusing than helpful. Such new words are technically called *neologisms* (literally, "new words"), and they're a habit of mine. Don't worry, though; I'll clarify each and every one of them as we encounter them.

## Science Adjacent

Adjacent: next to, nearby, close to, *almost*. Pretty much everything here is based on hard science (and I'll tell you if something isn't), but some parts of the science (especially exoplanet classification) is still catching up with the needs of speculation and entertainment. (I don't know about you, but I'm holding my breath for the day the International Astronomical Union -- yes, the ones who slapped down Pluto -- adopt "Class M" to describe planets with nitrogen-oxygen atmospheres.) That's where a lot of the neologisms will come into play.

The point, here, is that this is not intended to be an accurate description of the actual universe (that's what cosmology, astronomy, etc. are there for). This is a system designed to be *based on* hard science, but flexible enough for speculative and fictive uses. If you don't like a shortcut or an embellishment I've included, ignore it.

#### **Because I Say So**

Which brings me to a little Latin motto I like to keep on hand for those times when the scenario needs something science says a firm "no" to: *Quia ita dico* (kwee-uh ee-tah dee-koh). It literally means, "Because I say so." It can be abbreviated QID (reminiscent of QED), and it is your best friend and strongest ally. Do you design 90% real-world accurate and then pronounce QID over it and keep going. Hey, if your players or readers want to stop and take the time to do the math to "prove you wrong", it's their time to take. Jus' sayin'.

This comes with two shortcut forms:

- 1. Quia est fictiae (kwee-uh est fik-tee-ai; QEF): "Because it is fictional"
- 2. Quia est phantasiae (kwee-uh est fan-tahs-ee-ai; QEP): "Because it is fantasy"

The first variant has broader application, as it can refer generally to any kind of fiction; the second is more specific (and perhaps adamantly) referential to works of fantasy, where "We don't need no stinking rules" is often the order of the day.

One other little Latin gem

Mundus tuum est (mun-dus too-um est): "It's your world".

Shall we get started?

# 0.02 Glossary of Thesiastics Glossary of Thesiastics

Thesiastics (n.)

/ˌθiziˈæstɪks/

The discipline of world-setting: the synthesis of structural systems, symbolic meaning, and contextual coherence into a fictional world. From Greek *thesis* ( $\theta \dot{\epsilon} \sigma \dot{\varsigma}$ ), "a placing or proposition."

#### Thesiast (n.)

One who engages in thesiastics. A worldbuilder by craft, choice, or obsession.

#### Enthesiast (n.)

A joyful or compulsive thesiast; one who takes irrepressible delight in the generative act of worldcrafting. Often found lost in topography, orbital diagrams, or comparative alphabets. See also: "lore architect", "cosmogenic maximalist", "inhabitant of their own draft folder."

#### Numerothesiastics (n.)

The quantitative branch of thesiastics. Concerned with the mathematical, physical, astronomical, and systemic underpinnings of worlds.

Abbreviated: T<sub>n</sub>

#### Mirandothesiastics (n.)

The qualitative branch of thesiastics. Concerned with myth, meaning, culture, aesthetics, and affective resonance.

Abbreviated: T<sub>m</sub>

#### $T_n / T_m$

Subscript notation used throughout W101 to refer respectively to numerothesiastic and mirandothesiastic domains.

## **Ontosomics**

## **What Is Ontosomics?**

**Ontosomics** is the symbolic and classificatory study of *life-relevant planetary characteristics*, with an emphasis on environmental, structural, and energetic conditions that affect **habitability** or **biosignature potential**.

**From Greek**: *ontos* (being, existence) + *sōma* (body) + *-ics* (systematic study)

## **Q** Working Definition (WBN)

**Ontosomics** is the study of planetary and environmental features as they relate to the possibility, probability, or support of life — whether Earthlike, analogous, or entirely exotic.

It operates as the **biospheric inference layer** in WBN's planetary modeling system — situated between:

- Astrophysics (e.g. stellar irradiance, orbital parameters)
- Geophysics (e.g. mass, magnetosphere, atmosphere)
- **Exobiology** (life models, chemistry, thermodynamics)

## 🔧 Ontosomic Tools in WBN

Tool / Concept	Purpose
Geotic Envelope	Defines a planemo's physical suitability for Earthlike life
Thermozones	Classifies stellar orbits by thermal habitability
Xenotic / Parahabitable / Habitable / Hospitable	Ontozone classification system
Magnetosphere Estimation	Models shielding effects from solar radiation
Atmospheric Criteria	Pressure, composition, retention against thermal escape
Albedo Modeling	Determines heat balance and climate potential
Hydrospheric Patterns	Classifies land–ocean balance for surface stability
Anthropic Norm	Reference point based on Earth-standard conditions

## **Solution** Solution Soluti

Ontosomics does not presume or require biology as we know it — instead, it defines the **envelopes and thresholds** within which life *might* emerge, persist, or adapt.

It is **not** a guarantee of life — only of **viability zones**, **environmental plausibility**, and **symbolically tractable models**.

## **Page Title Goes Here**

## Numerical Precision and Rounding Conventions

Unless otherwise noted, decimal values in *Worldcrafting 101* are expressed to **three decimal places**, including trailing zeros (e.g.,  $\langle 1.000 \land 0.500 \rangle$ ). This standard ensures clarity and consistency across all parameter outputs and computational examples.

In some cases, a **fourth decimal place** is included — **not** to imply increased precision, but to clarify the **rounding direction** of the third decimal digit:

- 0.5445 indicates that the third-place digit (4) would round **up** to 0.545, making the standard value a **slight overstatement**.
- 0.5454 shows that rounding to 0.545 is a **safe approximation**, as the third-place digit has **not been rounded up**.

#### <u>Sidebar — Range Constraints & Random Assignment</u>

"Gaean" is a composite designator for planets identical to Earth in all particulars except land-towater surface ratio, rotation rate, and/or orbital period, and fall under the Terrean planemo type. Axial tilt can also vary within Earth's standard range of 22.1° - 24.5°. Since orbital period may vary, orbital eccentricity may, as well.

- **Geotics**: Earth-cognate planets with differences that still allow for human habitation with technological aid (habitable).
- Rheatics: Earth-analogs—hospitable planets nearly identical to Earth in composition, surface conditions, and other major characteristics, except for minor variations in Characteristics and Attributes.
- Gaeans: "Hospitable" Earth-correlates—planets that are compositionally identical to Earth in mass, density, radius, surface gravity, atmospheric composition, and overall environment, with potential variations in surface features, climate, or orbital dynamics.

Mansible: occupiable, tenantable, but not inherently hospitable or habitable.

Terrene

**Terrestrial** 

Terranean

#### README

## WorldCrafting101: A Science-Adjacent **Worldbuilding Toolkit**

"Because sometimes you just want to build a world you can actually use."



## Project Purpose

WorldCrafting101 is a self-paced, science-adjacent toolkit for worldbuilders, writers, game masters, and simulation enthusiasts who want to design plausible planets, stars, and systems — without needing a physics degree.

This guide balances scientific plausibility with creative flexibility, delivering fully worked formulas, step-by-step examples, and enough explanation that readers understand both what they're doing and why they're doing it.

**Sed ego dico.** — Because I say so. **Sed phantasiae.** — Because... fantasy. **Mundus tuum est.** — It's your world.

## Nhat You'll Need

- Basic algebra
- Occasional trigonometry (fully explained)
- Familiarity with spreadsheets (helpful, not required)
- Curiosity and willingness to experiment

No calculus. No hand-waving. Fully narrated examples accompany every formula.



To make this guide a little more fun (and hopefully a little more helpful), you'll occasionally encounter two recurring voices:

- Hiparistarchus Ptolemeus Galileopernicum ("Hippy") Our conservative traditionalist.
   He clings to classical models, worries about edge cases, and politely nags about technical details.
- Keplarius Braheus ("Keppy") Our enthusiastic challenger. He eagerly asks "What if we
  push this?" and loves playing with edge cases and speculative scenarios.

Think of them as your study buddies — they raise the kinds of questions you're likely thinking as we work through models together.



#### Module Structure

Module	Description
01 — Habitable Planet Builder	Build an Earthlike world step-by-step
02 — Planetary Systems	Build full star systems (coming soon)
03 — Stellar Classes	Classify stars and define habitable zones (coming soon)
04 — Moons & Satellites	Add moons, Roche limits, and stability zones (coming soon)

## \*

## **Attribution Note**

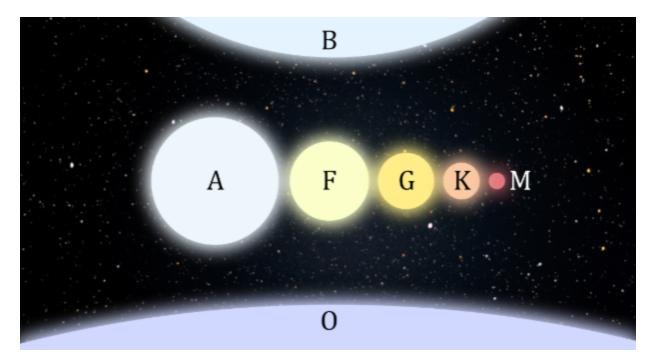
This project adapts and synthesizes models from published astrophysics and planetary science sources. Where science leaves gaps, creative extensions are introduced transparently for worldbuilding purposes.

If you believe any source has been overlooked or attribution could be improved, feel free to open an issue — corrections are always welcome.



## M002 - Stars — 00 Compendium

M002 - Stars — 01 Spectral Classes



## Stars and Spectral Classes: The Fusion-Fueled Continuum

First: The spectral class system used throughout this guide — the sequence **O**, **B**, **A**, **F**, **G**, **K**, **M** — is historically rooted in the observational astronomy of the late 19th and early 20th centuries. Its peculiar alphabetical order reflects the evolution of stellar classification from empirical cataloging to physical understanding.

For readers curious about its origins — including the critical work of **Annie Jump Cannon**, **Cecilia Payne-Gaposchkin**, and the less brilliant men who received most of the credit — see <u>Sidebar: The Spectral System and the Women Who Built It</u>.

Second: The spectral classes used in WBN are based on a **linearized temperature model**. This approach smooths over the irregularities of the traditional system to support clean interpolation, symbolic clarity, and consistent orbital modeling.

If you're curious about the limitations of the classical OBAFGKM system — and why we've chosen to "straighten the curve" — see <u>Sidebar Module: \_Mind the Gap — The Shortcomings of the Traditional Spectral Scale</u>.

## **Spectral Class Table**

Here are the spectral classes we'll be working with.

Spectral Class	Low Temp. (K)	High Temp. (K)
0	25000	55000
В	10000	25000
Α	7500	10000
F	6000	7500
G	5000	6000
K	3500	5000
M	2400	3500
Brown ↓ Dwarfs ↓		
L	1300	2400
Т	600	1300
Y	300	600

#### Notes:

- Spectral Classes L, T, and Y are "special cases" which are covered in detail in another module (\langle insert module name here \rangle)
- Each range reflects a star's **surface temperature**, typically noted as  $T_{\rm eff}$  in astronomical literature.
- In WBN:
  - **K** = temperature in Kelvin
  - **T** = temperature *relative to the Sun* (i.e., ⊙ = 5800K ⇒ T = 1.0)

## Spectral Type

Each spectral class is subdivided into 10 **spectral types**, numbered **0** (hottest) to **9** (coolest).

Hippy: Wait, that's -

Yes, it runs backwards. No, we're not happy about it, either (don't shoot the messenger).

For example:

The Sun, at 5800K, is classified as a G2 star —

Spectral Class: G

• Spectral Type: 2

#### **Note on Spectral Type Precision in WBN**

In this system, a **spectral type** is defined by its **numerical position** within a spectral class. For example:

- G2, G2.3, and G2.9 are all Type 2
- The decimal simply adds interpolation precision it does **not** define a new type.
- Therefore, **Type 2** refers to the full range ⟨2.0 ∧ 2.999···⟩ within class *G*.

This allows for relatively simple mathematical treatment of the relationship between spectral type (T) and surface temperature (K).

$$\mathcal{E} = \frac{\kappa - K}{b}$$

$$\kappa = \mathcal{Z} p + K$$

$$K=\kappa-\mathcal{E} p$$

$$p = \frac{\kappa - K}{2}$$

Where:

- K = the star's surface temperature in Kelvin
- κ = the *upper bound* temperature of the relevant spectral class
- b = the thermal interval constant for the relevant spectral class
- 2 = the spectral *type* number

#### The Thermal Interval Constant (b)

Where does b come from?

For a given spectral class b can be calculated by:

$$b = \frac{high\ temp - low\ temp}{10}$$

Here is the above table with these constants added:

Spectral Class	Low Temp. (Kelvin)	High Temp. (Kelvin)	Thermal Interval Constant (þ)
0	25000	55000	3000
В	10000	25000	1500
Α	7500	10000	250
F	6000	7500	150
G	5000	6000	100
K	3500	5000	150
М	2400	3500	110
L	1300	2400	110
Т	600	1300	70
Y	300	600	30

#### **Example**

Let's run the numbers for the Sun

- Known surface temperature: 5800K
- Checking the table, 5800K falls between 5000K and 6000K, so the Sun is spectral class
   G
- The high temperature ( $\kappa$ ) for spectral class G is  $\kappa$  6000K
- The thermal interval constant (b) for spectral class G is b = 100
- What is the Sun's spectral type (2)
   Running the numbers:

$$\mathcal{Z} = rac{\kappa - K}{p}$$
 $\mathcal{Z} = rac{6000 - 5800}{100}$ 
 $\mathcal{Z} = rac{200}{100}$ 
 $\mathcal{Z} = 2 \checkmark$ 

The Sun is spectral type *G2*.

#### Reversing the process:

• The known spectral class of the Sun is G

- The known spectral type of the Sun is 2 = 2
- The high temperature (κ) for spectral class G is κ 6000K
- The thermal interval constant (b) for spectral class G is b = 100
- What is the Sun's Kelvin temperature (K)
   Running the numbers:

$$K = \kappa - 2h$$
  
 $K = 6000 - (2)(100)$   
 $K = 6000 - 200$   
 $K = 5800 \checkmark$ 

The surface temperature of the Sun is 5800K.

## Converting Between Absolute Kelvin (K) And Solar Relative (T)

Nothing could be simpler:

$$T = \frac{K}{5800}$$

$$K = 5800T$$

For instance: the Sun's surface temperature is K = 5800:

$$T = \frac{K}{5800} = \frac{5800}{5800} = 1 \checkmark$$

Conversely, the Sun's relative temperature is T = 1.0:

$$K = 5800T = (5800)(1) = 5800 \checkmark$$

#### **Fictional Examples**

Let's say we have a star called Essem that we want to be spectral type *F3.65*. What is its Kelvin temperature?

- The surface temperature for spectral class F is  $K \in \langle 6000 \land 7500 \rangle$ .
- The thermal interval constant for spectral class F is β = 150.
   Working through the equation:

$$K = \kappa - 2h$$
  
 $K = 7500 - (3.65)(150)$   
 $K = 7500 - 547.5$   
 $K = 6952.5 \checkmark$ 

What is Essem's relative surface temperature?

$$T = \frac{K}{5800}$$

$$T = \frac{6952.5}{5800}$$

$$T = 1.199 \checkmark$$

Essem's relative temperature is  $T = 1.199 \odot$ .

#### **Working The Other Direction**

Let us say that Essem has a near neighbor, Essel, and we know that its relative temperature is  $T = 0.876 \odot$ . What is its spectral type?

First, convert T to K by:

$$K = 5800T = (5800)(0.876) = 5080.8 \checkmark$$

Looking at our table we see that this value falls in spectral class G:

Spectral Class	Low Temp. (Kelvin)	High Temp. (Kelvin)	Thermal Interval Constant (þ)
G	5000	6000	100

... which gives us all the other information we need:

- G-class high temperature is κ = 6000
- G-class thermal interval constant is b = 100

The spectral type is:

$$\mathcal{Z} = rac{\kappa - K}{b}$$

$$\textit{2} = \frac{6000 - 5080.8}{100}$$

$$\mathcal{Z} = \frac{919.2}{100}$$

$$Z = 9.192 \, \checkmark$$

Essel's spectral type is G9.192.

## **Parameter Ranges By Spectral Class**

	SC →	0	В	Α	F	G	K	M
	High	55000	25000	10000	7500	6000	5000	3500
Kelvin	Mean	40000	17500	8750	6750	5500	4250	2950
	Low	25000	10000	7500	6000	5000	3500	2400
	TIC¹ ( <i>þ</i> )	3000	1500	250	150	100	150	110
	High	9.4828	4.3103	1.7241	1.2931	1.0345	0.8621	0.6034
T⊙	Mean	6.8966	3.0172	1.5086	1.1638	0.9483	0.7328	0.5086
	Low	4.3103	1.7241	1.2931	1.0345	0.8621	0.6034	0.4138
	High	17.0690	7.7586	3.1034	2.3276	1.8621	1.5517	1.0862
R⊙	Mean	12.4138	5.4310	2.7155	2.0948	1.7069	1.3190	0.9155
	Low	7.7586	3.1034	2.3276	1.8621	1.5517	1.0862	0.7448
	High	2.356 M	20.779 k	85.1093	15.1476	3.9709	1.3298	0.1565
L⊙	Mean	348.608 k	2.445 k	38.1967	8.0501	2.3559	0.5015	0.0561
	Low	20.779 k	85.109	15.1476	3.9709	1.3298	0.1565	0.0163
	High	18.7759	8.5345	3.4138	2.5603	2.0483	1.7069	1.1948
M⊙	Mean	13.6552	5.9741	2.9871	2.3043	1.8776	1.4509	1.0071
	Low	8.5345	3.4138	2.5603	2.0483	1.7069	1.1948	0.8193
	High	64.10E- 06	4.00E- 03	0.1280	0.4684	1.3041	4.7336	29.3785
Q⊙	Mean	0.67E-03	65.64E- 03	0.2766	0.8441	2.1003	12.4968	82.4297
	Low	0.69E-06	35.57E- 06	3.47E- 03	0.0146	0.0447	0.1112	0.6614

<sup>&</sup>lt;sup>1</sup> Thermal Interval Constant

M002 - Stars — 02 Parameters

## **Stellar Parametrics**

In M002 - Stars — 01 Spectral Classes, we covered spectral classes and spectral types and their association to the surface temperatures of stars. Stars, like planemos, have a basic set of parameters that describe them:

- Temperature How hot is the surface?
  - Absolute measure: Kelvin (K)
  - Relative measure: Solar units (T)
- Mass How much material is there? (M)
- Luminosity How bright is it? (L)
- Radius How big is it? (R)
- Lifetime How long does it shine? (Q)
  - Chiefly relevant to Main Sequence stars, particularly stars that are Solar Cognates (more on this below.)

#### Notes:

- 1. Where we use lower-case letters for the parameters of planemos, we use uppercase letters for stars, so it's easy to tell them apart.
- 2. While **mass** (m) is the primary parameter for planets, with **density** ( $\rho$ ) secondary, for stars **Temperature** (T) is the primary parameter, and **radius** (R) is secondary.
  - While luminosity is technically derived from a star's temperature and radius
    (see the Stefan-Boltzmann Law, below), it plays a central role in modeling
    stellar systems particularly when calculating orbit distances, habitable zones,
    and irradiance. In practice, it's often treated as the secondary parameter after
    termperature for thesisastics.

## **Equations of State**

A regularized set of empirical relationships can be used to estimate any stellar parameter from the others — assuming a Main Sequence **blackbody**-like star (see <u>Sidebar — What Is The Main Sequence</u>).

Keppy: And a blackbody is ...?

Excellent question! A blackbody is an idealized physical object that:

- 1. **Absorbs all** incoming electromagnetic radiation no reflection, no transmission.
- 2. **Emits radiation** purely based on its temperature not its material, shape, or color.

3. Emits a **perfectly smooth, continuous spectrum** (a "thermal spectrum"). In short:

A blackbody is the theoretical gold standard for radiant heat emission — a perfect radiator and absorber.

#### Why "Blackbody" Matters Here

Most stars (especially Main Sequence stars) behave **approximately like blackbodies**, meaning their energy output can be modeled using **temperature alone**. This makes them excellent candidates for:

- Temperature-based modeling
- Color-temperature mapping (blue = hotter, red = cooler)
- Spectrum-based classification (like spectral classes O–M)
- Real-World Deviation
  - Planets, dust clouds, and even stars aren't *perfect* blackbodies.
  - Real objects have an **emissivity** ε between 0 and 1:

$$F = \varepsilon \sigma T^4$$

But stars are close enough that the blackbody approximation works very well.

Hippy: Sorry you asked, Keplarius?

Yes, that's a bit technical and complicated, but it's also extremely *important* to what comes next.

Here are the promised equations:

Temperature (T)	Mass (M)	Radius (R)	Lifetime (Q)
$T=\sqrt[1.98]{M}$	$M=\sqrt[0.9]{R}$	$R=M^{0.9}$	$Q=M^{-2.5}$
$T=\sqrt[1.8]{R}$	$M=T^{1.98}$	$R=T^{1.8}$	$Qpprox{^{-0.36}\!\sqrt{R}}$
$T=Q^{-0.2}$	$M=Q^{-0.4}$	$R = Q^{-0.36}$	$Q=T^{-5}$

#### NOTE:

All of the above equations are *approximations*; stars are a much more variable set of objects (after all, they're mostly gas and plasma, so fluid dynamics plays a major role in their characteristics). These equations work **best** *in general* **for main sequence stars** of all classes.

**Keppy**: You said Luminosity was the second most important parameter for stars, but it doesn't appear in the table...?

Well spotted, Keppy! There's a reason.

#### The Stefan-Boltzmann Law

The Stefan-Boltzmann Law is a formulation that relates the **luminosity** of any luminous object to its **temperature** and **surface area**:

$$L=4\pi R^2\sigma T^4$$

Where:

- 4πR² = the surface area of the body
- T = is the temperature of the body in Kelvin
- σ = the Stefan-Boltzmann constant
  - $\sigma = 5.670374419 \times 10^{-8} Wm^{-2}K^{-4}$ 
    - Watts per square meter per Kelvin to the fourth power 1 K4
    - It tells you how much radiant energy per second (i.e., power) is emitted by a
       1 square meter portion of a perfect blackbody at 1 K<sup>4</sup>.

And this is why we needed the quick aside into the term "blackbody" earlier.

In thesiastics terms, we can simplify the Stefan-Boltzmann equation to:

$$rac{L_s}{L_{Sun}} = igg(rac{R_s}{R_{Sun}}igg)^2igg(rac{K_s}{K_{Sun}}igg)^4$$

Where:

- $L_S$  = the absolute luminosity of the star
- $L_{Sun}$  = the absolute luminosity of the Sun
- $R_S$  = the absolute radius of the star
- $R_{Sun}$  = the absolute radius of the Sun
- $K_S$  = the Kelvin temperature of the star
- $K_{Sun}$  = the Kelvin temperature of the Sun

Because the form  $\frac{X_s}{X_{Sun}}$  is the standard for converting a parameter to solar units, and  $K_s$ 

$$T=rac{K_s}{K_{Sun}}$$
 , this equation becomes:

$$L = R^2 T^4$$
, with derivations of

$$R=rac{\sqrt{L}}{T^2}, \qquad T=\sqrt[4]{rac{L}{R^2}}$$

## **Parameter Calculation Precedence**

The above being the case, there is a "best" order for calculating stellar parameters when starting from any given parameter (though it is always best start with K or T whenever possible).

All parameters (except K) are expressed in Solar-relative units; that is,  $T = 1 \odot$  for 5800 K,  $R = 1 \odot$  for the solar radius, etc.

#### Starting with Temperature (T) or (K)

Primary dependency chain:  $T/K \rightarrow R \rightarrow L \rightarrow M \rightarrow Q$ 

$$T=rac{K}{5800} \quad or \quad K=5800T$$
  $R=T^{1.8}$   $L=R^2T^4$   $M=T^{1.98} \quad or \quad M=\sqrt[0.9]{R}$   $Q=T^{-5} \quad or \quad Q=M^{-2.5}$ 

#### Starting with Mass (M)

Primary dependency chain:  $M \to T/K \to R \to L \to Q$ 

$$T=\sqrt[1.98]{M} \ K=5800T \ R=T^{1.8} \ \ or \ \ R=M^{0.9} \ L=R^2T^4 \ Q=T^{-5} \ \ or \ \ Q=M^{-2.5}$$

#### Starting with Radius (R)

Primary dependency chain:  $R \to T \to K \to L \to M \to Q$ 

$$T=\sqrt[1.8]{R} \ K=5800T \ L=R^2T^4 \ M=T^{1.98} \ Q=T^{-5} \ \ or \ \ Q=M^{-2.5}$$

#### Starting With Luminosity (L)

#### Primary dependency chain: $L \rightarrow T \rightarrow K \rightarrow R \rightarrow M \rightarrow Q$

$$T=\sqrt[7.6]{L} \ K=5800T \ R=T^{1.8} \ M=T^{1.98} \ Q=T^{-5} \ \ or \ \ Q=M^{-2.5}$$

#### Starting with Lifetime (Q)

\*As soon as you assume you'd never want to do this, you'll find a case for doing it.\* **Primary dependency chain**:  $Q \to T \to K \to R \to L \to M$ 

$$T=Q^{-0.2}$$
 $K=5800T$ 
 $R=Q^{-0.36}$ 
 $L=R^2T^4$ 
 $M=\sqrt[3]{L}$ 

M002 - Stars — 03 The Nucleal Orbit

#### The Nucleal Orbit

The average distance from Earth to the Sun — about  $1.496 \times 10^8$  km — is defined as one **astronomical unit (AU)**. Due to Earth's slightly elliptical orbit, this distance varies by approximately  $\pm 2.5$  million km between Earth's closest approach to and farthest distance from the Sun.

So, for all practical (and thesiastic) purposes the Earth's orbital distance (a) is a = 1.0AU. In fact a is the commonly used symbol for any orbital distance when it is expressed in Astronomical Units.

For our purposes, I have revived an old word from the dusty backroom shelves of English — *nucleal* — and given it new life:

**Nucleal Orbit** (N): the orbital distance from any given star at which a planet receives the same stellar irradiance as Earth receives from the Sun at 1 AU.

... and given it the utterly unimaginative symbol, N.

The important thing to note here is that *N* is not constant, but varies from star to star, and it is calculated by:

$$N = \sqrt{L}$$

Where:

• L = the Luminosity of the star in relative units

Obviously for the Sun:

$$N = \sqrt{L} = \sqrt{1} = 1$$

Keppy: So for a dimmer star N shifts closer to the star?

**Hippy**: And for a brighter star, it shifts farther out from the star.

Correct on both counts. And once we know N, we can express the **habitable zone** (details coming!) as a proportional range around it. For instance, for a star of half the Sun's luminosity  $L=0.5\odot$ :

$$N = \sqrt{L} = \sqrt{0.5} = 0.7071 \; AU$$

#### The Nucleal Orbit and the Habitable Zone

A quick survey of the existing literature reveals a commonly held definition for the **habitable zone** as:

$$\langle 0.950 \wedge 1.385 \rangle N$$

... or, in other words: between 95% of the nucleal orbit distance to 1.385 times (138.5%) the nucleal orbit distance. In the case of our hypothetical  $L=0.5\odot$  star and its N=0.7071~AU nucleal orbit, the range of its habitable zone calculates to:

$$N = 0.7071 \; AU$$
 Inner Edge =  $0.950N = (0.950)(0.7071) = 0.6717 \; AU$  Outer Edge =  $1.385N = (1.385)(0.7071) = 0.9793 \; AU$ 

**Keppy**: So ... the *outer edge* of this star's habitable zone is *closer to its star* than *Earth orbits from the Sun*.....

Exactly. But, this region is only a part of a total star system.

#### The Ontozones – Two Habitable Zones

To start with, some scientist posit a wider, more "optimistic habitable zone" region, covering:

$$\langle 0.750 \wedge 1.770 \rangle N$$

For our purposes, we call this *wider spread* the actual **habitable zone** and we call the narrower span the **hospitable zone**, so that the *hospitable zone* comprises a middle lane between the extremes of the *habitable zone*:

$$rac{1.385 - 0.95}{1.77 - 0.75} = rac{0.435}{1.02} = 0.4265 \; AU$$

... about 42.65% of it, in fact.

Orbital Range	Ontozones
⟨0.750 ∧ 0.950⟩N	Habitable Zone
⟨0.950 ∧ 1.385⟩N	Hospitable Zone
⟨1.385 ∧ 1.770⟩N	Habitable Zone

It has also been suggested that "desert" planets (think Dune, Tattooine) might orbit in the zone between  $\langle 0.500 \land 0.750 \rangle$ N and we might call this the "desert planet zone", which would be, by definition, **parahabitable** to **habitable** (but mostly the former).

Orbital Range	Ontozones
⟨0.500 ∧ 0.750⟩N	Parahabitable
⟨0.750 ∧ 0.950⟩N	Habitable Zone
⟨0.950 ∧ 1.385⟩N	Hospitable Zone
⟨1.385 ∧ 1.770⟩N	Habitable Zone

## The Frost Line (F)

Research indicates that beyond a distance of about  $a=4.850\ AU$  in our Solar system, water cannot remain liquid due to insufficient irradiance from the Sun. This distance is sometimes termed the "Frost Line" or "Ice Line", and an orbital distance of a=4.850N is the value we set for this outer limit.

#### For instance:

- Mars' orbit in our own Solar system is  $a=1.524\ AU$ , well within the 1.770N limit
- The asteroid belt is ≈ ⟨2.2 ∧ 3.2⟩AU, beyond 1.77N, but still within the 4.850 AU F limit.
   This region in our Solar system does not host a sizeable planemo (and likely never did), but if one were to exist there, it would probably be parahabitable due to the orbital distance from the Sun.

This gives us another range of orbits we can add to our accounting:

Orbital Range	Ontozones
⟨0.500 ∧ 0.750⟩N	Parahabitable
⟨0.750 ∧ 0.950⟩N	Habitable Zone
⟨0.950 ∧ 1.385⟩N	Hospitable Zone
⟨1.385 ∧ 1.770⟩N	Habitable Zone
⟨1.770 ∧ 4.850⟩N	Parahabitable

Jupiter's orbit is at  $a=5.204\ AU$ , well beyond the  $4.850\ AU$  limit, and things just get colder from there, so we can specify that if any kind of "life" does exist in this region it is likely to be extremophile by Earth standards, which WBN denotes as "**xenotic**".

Orbital Range	Ontozones
⟨0.500 ∧ 0.750⟩N	Parahabitable
⟨0.750 ∧ 0.950⟩N	Habitable Zone
⟨0.950 ∧ 1.385⟩N	Hospitable Zone
⟨1.385 ∧ 1.770⟩N	Habitable Zone
⟨1.770 ∧ 4.850⟩N	Parahabitable
4.850N →	Xenotic

Similarly, any "life" that might come to be on a body orbiting closer than 0.500N would also be xenotic:

Orbital Range	Ontozones
← 0.500N	Xenotic
⟨0.500 ∧ 0.750⟩N	Parahabitable
⟨0.750 ∧ 0.950⟩N	Habitable Zone
⟨0.950 ∧ 1.385⟩N	Hospitable Zone
⟨1.385 ∧ 1.770⟩N	Habitable Zone
⟨1.770 ∧ 4.850⟩N	Parahabitable
4.850N →	Xenotic

Finally, we differentiate between inner and outer zones, and define notations for each:

Orbital Range	Ontozones	Notation
← 0.500N	Inner Xenotic Zone	$Z_{IX}$
⟨0.500 ∧ 0.750⟩N	Inner Parahabitable Zone	$Z_{IP}$

Orbital Range	Ontozones	Notation
⟨0.750 ∧ 0.950⟩N	Inner Habitable Zone	$Z_{IH}$
⟨0.950 ∧ 1.385⟩N	Hospitable Zone	$Z_H$
⟨1.385 ∧ 1.770⟩N	Outer Habitable Zone	$Z_{OH}$
⟨1.770 ∧ 4.850⟩N	Outer Parahabitable Zone	$Z_{OP}$
4.850N →	Outer Xenotic Zone	$Z_{OX}$

This gives us a full inventory of orbital limits for any star system we choose to devise.

M002 - Stars — 04 Thermozone Orbits

## **Star System Thermozones**

We've already introduced the term Habitable Zone before, sometimes also prosaically referred to as "The Goldilocks Zone".

**Hippy**: Silliness!

Well.... Scientists do try to keep things accessible for those not familiar with the official lingo.

Anyway, broadly speaking, this is the range of orbital distances around a given star in which an orbiting planemo might reasonably be expected to retain liquid water and a reasonably dense atmospheric envelope. In the previous section, we defined the *parahabitable*, *habitable*, and *hospitable* zones as occupying this region.

Keppy: But this is based on ... what?

I'm glad you asked; it's based on how much energy (irradiance) the planet receives from its star compared to how much insolation the Earth receives from the Sun (you may remember this concept from our discussion of the *nucleal orbit*. And *that* gives us our standard candle (if you'll pardon the pun).

## Naming The Zones And Labeling Their Limits

#### The Thermozones

For ease of remembering these zones and their ontosomic characteristics we use the **thermozone** naming system:

Thermozone	Orbital Range	Ontozones	Notation	
Igniozone	← 0.500N	Inner Xenotic Zone	$Z_{IX}$	"Desert Planet Zone"
Calorozone	⟨0.500 ∧ 0.750⟩N	Inner Parahabitable Zone	$Z_{IP}$	
Heliozone	⟨0.750 ∧ 0.950⟩N	Inner Habitable Zone	$Z_{IH}$	
Solarazone	⟨0.950 ∧ 1.385⟩N	Hospitable Zone	$Z_H$	
Hiberozone	⟨1.385 ∧ 1.770⟩N	Outer Habitable Zone	$Z_{OH}$	
Brumazone	⟨1.770 ∧ 4.850⟩N	Outer Parahabitable Zone	$Z_{OP}$	
Cryozone	4.850N →	Outer Xenotic Zone	$Z_{OX}$	"Glacier Planet Zone"

#### These names are derived from:

• Igniozone: Latin ignis, "fire"

Calorozone: Latin calor, "hot, heat"

• Heliozone: Greek Helios, an early name of the Sun god

- Planemos in this region might be somewhat Earth-like in environment, but generally warmer\*
- Solarazone: Latin solar, from Sol, a title of the Sun god
  - Planemos in this region are likely to be very Earth-like in their environment\*

• Hiberozone: Latin hiberno, "cold"

• Brumazone: Latin bruma, "winter"

• Cryozone: Greek kryo, "cold"

#### **Thermozone Limit Notation**

For ease of reference, the limiting orbital distances of the thermozones are denoted by an *H* accompanied by a subscript:

Notation	Orbital Distance
H <sub>o</sub>	0.500N
H <sub>1</sub>	0.750N

<sup>\*</sup> Assuming they are otherwise Earth-like in size and composition.

Notation	Orbital Distance
H <sub>2</sub>	0.950N
H <sub>3</sub>	1.385N
H <sub>4</sub>	1.770N
H <sub>5</sub>	4.850N

#### Adding these to our earlier table:

Thermozone	Zone Limits	Orbital Range	Ontozones	Notation	
Igniozone	← H <sub>0</sub>	← 0.500N	Inner Xenotic Zone	$Z_{IX}$	"Desert Planet Zone"
Calorozone	$\langle H_0 \wedge H_1 \rangle$	⟨0.500 ∧ 0.750⟩N	Inner Parahabitable Zone	$Z_{IP}$	
Heliozone	$\langle H_1 \wedge H_2 \rangle$	⟨0.750 ∧ 0.950⟩N	Inner Habitable Zone	$Z_{IH}$	
Solarazone	$\langle H_2 \wedge H_3 \rangle$	⟨0.950 ∧ 1.385⟩N	Hospitable Zone	$Z_H$	
Hiberozone	$\langle H_3 \wedge H_4 \rangle$	⟨1.385 ∧ 1.770⟩N	Outer Habitable Zone	$Z_{OH}$	
Brumazone	$\langle H_4 \wedge H_5 \rangle$	⟨1.770 ∧ 4.850⟩N	Outer Parahabitable Zone	$Z_{OP}$	
Cryozone	$H_{5} \rightarrow$	4.850N →	Outer Xenotic Zone	$Z_{OX}$	"Glaci Planet Zone"

This gives us a very robust way of discussing orbital distances in any star system.

Note that the *nucleal orbit*, being always N=1.0N, always falls within the Solarazone. In fact, it always falls at 11.49% *into* the Solarazone from its inner edge.

M002 - Stars — 05 The Perannual Orbit

## **The Perannual Orbit**

There is one remaining essential star system orbit, which I have called the **perannual** orbit. The word comes from the Latin *per annum*, meaning "per year" or "each year", and the

name reflects that this is the orbit in any star system which has an orbital period (P) of exactly one Earth year.

#### IMPORTANT

"One Earth Year" in this case is the duration of Earth's complete orbit around the Sun relative to the larger reference frame of the "fixed" stars; thus this is called the **sidereal year**, from the Latin *sidus*, "star". This is measured and denoted in terms of **ephemeris days** — which are *defined* to be exactly 86400 *seconds* in duration. Thus, the sidereal year (and, consequently, the perannual year) has a duration of:

365.256363004 Ephemeris Days 
$$or$$
  $365^d 6^h 9^m 9.763545^s$ 

This is *not* a "year" as experienced by inhabitants on the surface of a planet on this orbit (that is called the **tropical year**, which is in part dependent upon the *rotational period* of the planet, itself); this is the **sidereal year**.

Please see <u>Sidebar — Units and Measures of Time</u> for a more in-depth discussion of this topic.

We denote the perannual year as A, and its location in the star system is not constant (the same as the nucleal orbit (N) but is determined by the mass of the star(s), and – to a small but measurable degree – by the mass of the planet.

Please see M002 - Stars — 06 Relating the Nucleal and Perannual Years for an in-depth exploration of this relationship.

The perannual orbit is determined not by the luminosity of the star(s) in the system but by **mass**, mostly of the stars(s), but the mass of the planemo can become a calculatory relevant factor if it is a significant fraction of the mass of the star(s).

The perannual orbit is an *orbital distance*, but it is predicated on the **period** of that orbit — how long it takes the planemo to complete one entire orbit (measured in Earth years). **ANY** planemo orbital period is calculated (in relative terms) by:

$$P=\sqrt{rac{a^3}{M+m}}$$
 
$$a=\sqrt[3]{P^2(M+m)}$$
  $M+m=rac{a^3}{P^2}$  Believe it or not, this has its uses

Where:

- *P* = the planemo's orbital period in Earth sidereal years
- a = the measure of the semi-major axis of the planemo's orbit
- *M* = the mass of the star(s) in Solar masses
- m = the mass of the planemo (also expressed in *Solar*) masses

In many cases (such as that of Earth), *m* is such a small number that it can be ignored without drastically altering the value of *P*. In the case of Earth:

- $M=1\odot$
- $m=0.000003003\odot$  (3.003 imes  $10^{-6}$ ) three *millionths* of the Sun's mass
- a=1 AU

Calculating with only the Sun's mass:

$$P=\sqrt{rac{a^3}{M}}=\sqrt{rac{1^3}{1}}=\sqrt{rac{1}{1}}=\sqrt{1}=1 ext{ years}$$

Calculating with both masses:

$$P = \sqrt{\frac{a^3}{M+m}}$$

$$= \sqrt{\frac{1^3}{1+0.000003003}}$$

$$= \sqrt{\frac{1}{1.000003003}}$$

$$= \sqrt{0.999997}$$

$$P = 0.9999985 \text{ years}$$

... a difference of about 47.384 seconds.

#### 

The *perannual orbit* defines the location in any star system where a planemo would complete one sidereal Earth year.

It may be closer-in than the nucleal orbit (**intranucleal**) or farther out than the nucleal orbit (**extranucleal**).

If it is ever the same as the nucleal orbit, then the star(s)' mass(es) must be  $M=1\odot$ , and — ideally — the planemo's mass must be  $m=1\bigoplus$ .

Unlike the *nucleal orbit* (which depends on *stellar irradiance*), the perannual orbit *depends only the mass of the system* — and serves as a *temporal* rather than *thermal* reference point.

As shown above, the *distance* of any orbit can be calculated from the period and the masses via:

$$a=\sqrt[3]{P^2(M+m)}$$

... but if we already know that P = 1, it drops out of the equation:

$$a=\sqrt[3]{M+m}$$

... such that the distance of the orbit is simply the cube-root of the sum of the masses.

For clarity, we denote the *distance* of the perannual orbit with an *A* (for *anno*), so our equation becomes:

$$A=\sqrt[3]{M+m}$$
 When taking into account both masses  $A=\sqrt[3]{M}$  When using only the central mass

#### M002 - Stars — 06 Relating the Nucleal and Perannual Years

We have explored both <u>The Nucleal Orbit</u> and <u>The Perannual Orbit</u>. These two are not *limiting distances*, but **orbital environs** which both describe and contribute to the ontosomic nature of planemos.

As a quick review:

Nucleal Orbit: that orbit (expressed in AU) at which a planemo receives from its star(s)
the same radiant flux as Earth receives from the Sun at one Astronomical Unit distance,
calculated by:

$$N=\sqrt{L}$$

Where L = Luminosity of the star(s) as expressed in Solar units,  $\odot$ 

 Perannual Orbit: that orbit (expressed in AU) which has an orbital period of exactly one sidereal Earth year, calculated by:

$$A=\sqrt[3]{M+m}$$

If we disregard the mass of the planemo *m*:

$$A=\sqrt[3]{M}$$

And we saw in M002 - Stars — 02 Parameters that through relationship:

$$M = \sqrt[3]{L}$$

This means that:

• The perannual orbit can be *approximated* directly from the luminosity by:

$$Approx\sqrt[3]{\overline{L}}pprox\sqrt[6]{L}$$

• The nucleal orbit can be approximated directly from the mass by:

$$Npprox\sqrt{M^3}$$

And, by extension either can be *approximated* from the other by:

$$Approx \sqrt[6]{N^2}pprox \sqrt[3]{N} 
onumber \ Npprox A^3$$

#### REMEMBER

- Both N and A are measured in astronomical units, not time!
- These last four equations are **approximations**; in most cases they'll be "accurate enough", but calculating *N* and *A* robustly is always advised.

M002 - Stars — 07 Fine-tuning Stellar Parameters

# Stars — 2.07 Fine-tuning Stellar Parameters Standard Parameter Equations

The Standard Parameter Equations (see M002 - Stars — 02 Parameters):

Temperature (T)	Mass (M)	Radius (R)	Lifetime (Q)
$T=\sqrt[1.98]{M}$	$M=\sqrt[0.9]{R}$	$R=M^{0.9}$	$Q=M^{-2.5}$
$T=\sqrt[1.8]{R}$	$M=T^{1.98}$	$R=T^{1.8}$	$Qpprox{}^{-0.36}\!\sqrt{R}$
$T=Q^{-0.2}$	$M=Q^{-0.4}$	$R=Q^{-0.36}$	$Q=T^{-5}$

*generally* work well for most **Main Sequence** stars, but a survey of known stars in the Solar neighborhood —

Hippy: "Wha-"

... which is too complex and extensive to detail here — suggests that modest adjustments to a couple of key exponents yield parameter equations that better reflect observed stellar characteristics. Since thesiastics prioritizes plausible-world construction over strict theoretical purity, these revised values offer better performance across the mass range of interest.

#### **Modified Parameters Table**

Temperature (T)	Mass (M)	Radius (R)	Lifetime (Q)	Luminosity (L)
$T=\sqrt{M}$	$M=\sqrt[0.9]{R}$	$R=M^{0.9}$	$Q=M^{-2.5}$	$L=M^{3.8}$
$T=\sqrt[1.8]{R}$	$M=T^2$	$R=T^{1.8}$	$Qpprox{^{-0.36}}\!\!\!\sqrt{R}$	$Lpprox R^{4.ar{2}}$
$T=Q^{-0.2}$	$M=Q^{-0.4}$	$R=Q^{-0.36}$	$Q=T^{-5}$	$L=T^{7.6}$
$T=\sqrt[7.6]{L}$	$M=\sqrt[3.8]{L}$	$Rpprox \sqrt[4ar{2}]{L}$	$Q=L^{-1.52}$	$L=\sqrt[-1.52]{Q}$

#### Notes:

- The parameter relationship that changed from the previous table was  $T\leftrightarrow M$ , where the exponent increased slightly from 1.98 to 2.0
- The major change is the addition of direct calculation for the parameters to-and-from luminosity; these are included for the purpose of simplifying much of the math related to M002 - Stars — 08 `Sun-Like` Stars.
- For greatest accuracy:
  - The exponent 7.6 can be more precisely specified as 7.5778
  - The exponent 3.8 can be more precisely specified as 3.7889

M002 - Stars — 08 'Sun-Like' Stars

## Solar Analogs, Cognates, and Twins

The published literature often speaks of "solar analog" stars, but tends to be distressingly vague about exactly what the term means. Generally speaking, it means "a star very much like the Sun".

**Keppy**: And that doesn't help at all — that could mean *any* star, really.

You're right; so, for our purposes we have our own definitions, based on *orbits* and the ontozones. But, first, a survey of existing terminology.

## **Existing Definitions**

A "Sun-like star" is a broad term used to describe stars that share characteristics with our own Sun. Astronomers often categorize them into a hierarchy based on their *physical* similarity to the Sun. They all need to be main-sequence stars\*\*, actively fusing hydrogen into helium in their core, like our Sun. Otherwise:

**Solar-type Stars:** This is the broadest category. These stars are broadly similar to the Sun in mass and evolutionary state. Key characteristics include:

• Spectral type: Typically F8V (6300 K) to K2V (4700 K) — more on this below.

**Solar Analogs:** These stars are more similar to the Sun than general solar-type stars, conforming to stricter criteria:

 Temperature: Within approximately 500 Kelvin (K) of the Sun's temperature (which is about 5800 K) — between 5300 K (G7V) and 6300 K (F8V).

**Solar Twins:** This is the most restrictive category, for stars that are nearly identical to the Sun. The idea is that they are virtually indistinguishable from our Sun in as many ways as possible:

#### Temperature:

- Within a very narrow range, typically ±10 K of the Sun's temperature 5790 K
   (G2.1V) to 5810 K (G1.9V).
- Some definitions are even stricter, within ±5 K 5795 K (G2.05V) to 5805 K (G1.95V).

#### Age:

- 4.3 4.7 Gyr (The Sun's age ±200 Ma)
- Sometimes as tight as ±100 Ma, i.e., 4.4 4.6 Gyr

## A Proposed, Clearer System

For thesiastic purposes, our criteria need to be more related to the *habitability* of orbiting planemos than directly to physical similarity between stars. Therefore, WBN defines the following:

#### Solar Analogs:

• Stars whose *perannual orbits* fall within  $\langle 0.500, 4.850 \rangle$  AU, spanning from the Inner Parahabitable Zone to the Outer Parahabitable Zone (H<sub>0</sub> – H<sub>5</sub>).

#### Solar Cognates:

• Stars whose *perannual orbits* fall within  $\langle 0.750, 1.770 \rangle$  AU, spanning from the Inner Habitable Zone to the Outer Habitable Zone (H<sub>1</sub> – H<sub>4</sub>).

#### Solar Twins:

• Stars whose *perannual orbits* fall within  $\langle 0.950, 1.385 \rangle$  AU, spanning the Hospitable Zone (H<sub>2</sub> – H<sub>3</sub>).

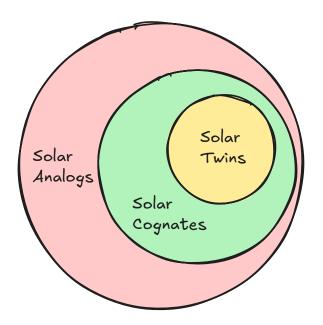
Thus:

- All Solar Twins are also Solar Cognates and Solar Analogs.
- All Solar Cognates are also Solar Analogs.
- Solar Analogs encompass the Solar Cognate and Solar Twin categories.

#### NOTE:

• This perannual-orbit-based requirement is largely arbitrary, predicated on the thesiastic idea that a planemo that is least different from Earth would have an orbital period the same as Earth's.

#### **Nested Ontozonal Categories of Sun-like Stars**



#### **Calculating The Spectral Types**

Previously, in M002 - Stars — 06 Relating the Nucleal and Perannual Years, we established that the *distance* of the perannual orbit can be approximated by:

$$A = \sqrt[3]{M}$$

... and in M002 - Stars — 07 Fine-tuning Stellar Parameters, we established the relationship:

$$L = M^{3.8}$$

... which lets us calculate that:

$$A=\sqrt[3]{\sqrt[3]{8}L}=\sqrt[114]{L}$$

In M002 - Stars — 04 Thermozone Orbits, we established that the thermozone limits are calculated by applying fixed scaling factors to the **nucleal orbit distance** (*N*), which is calculated from the square-root of the luminosity:

Limiting Orbit	Calculation
$H_0$	$0.500\sqrt{L}$
$H_1$	$0.750\sqrt{L}$
$H_2$	$0.950\sqrt{L}$
$H_3$	$1.385\sqrt{L}$
$H_4$	$1.770\sqrt{L}$
$H_5$	$4.850\sqrt{L}$

This means that we can set:

$$A=\sqrt[11.4]{L}$$
 equal to  $A=0.500\sqrt{L}$ 

... and solve for L:

$$egin{aligned} ^{11}\sqrt[4]{L} &= 0.500\sqrt{L} \ 0.500 &= rac{^{11}\sqrt[4]{L}}{\sqrt{L}} \ &= L^{rac{1}{11.4} - rac{1}{2}} \ &= L^{rac{2}{22.8} - rac{11.4}{22.8}} = L^{-rac{9.4}{22.8}} \ 0.500 &= L^{-0.4123} \ L &= rac{^{-0.4123}}{\sqrt[4]{0.500}} \ &= 5.372 \ \checkmark \end{aligned}$$

Converting luminosity to temperature:

$$T \equiv \sqrt[76]{L} \equiv \sqrt[7.6]{5.372} \equiv 1.248 \odot$$

In  $\underline{\text{M002 - Stars}}$  — 02 Parameters, we established the following relationship between solar-unit temperature (T) and Kelvin temperature (K)

So, our star has a Kelvin temperature of:

$$K = 5800T = 5800(1.248) = 7235.97 K$$

... and we can calculate the spectral class and type:

$$\mathcal{Z} = \frac{\kappa - K}{b}$$

Where:

• K = the star's surface temperature in Kelvin

• κ = the *upper bound* temperature of the relevant spectral class

• þ = the thermal interval constant for the relevant spectral class

• 2 = the spectral *type* number

Taken from the table:

Spectral Class	High Temp. (K)	Thermal Interval Constant (þ)
0	55000	3000
В	25000	1500
Α	10000	250
F	7500	150
G	6000	100
K	5000	150
M	3500	110
L	2400	110
Т	1300	70
Y	600	30

Our Kelvin temperature is  $7235.97\ K$  which is an F-type star, so

• κ = 7500

• b = 150

$$\mathcal{Z} = \frac{\kappa - K}{p} = \frac{7500 - 7235.97}{150} = \frac{264.03}{150} = 1.76$$

So the spectral type of a star with a perannual orbit at 0.500 AU is F 1.76 ✓.

## **Generalizing The Equation**

This logic can be extended for any  $H_x$  value:

By generalizing the scaling factor  $\lambda$ , we can calculate the relative stellar luminosity for **any** perannual orbit distance:

$$egin{aligned} ^{11.4}\!\!\sqrt{L} &= \lambda\sqrt{L} \ \lambda &= rac{^{11}\!\!\sqrt[4]{L}}{\sqrt{L}} \ &= L^{rac{1}{11.4} - rac{1}{2}} \ &= L^{rac{2}{22.8} - rac{11.4}{22.8}} = L^{-rac{9.4}{22.8}} \ \lambda &= L^{-0.4123} \ dots \; L &= rac{^{-0.4123}}{\sqrt[4]{\lambda}} \; \checkmark \end{aligned}$$

## **A Final Determination**

Substituting all of the  $H_x$  values in for  $\lambda$ :

Limiting Orbit	Scaling Factor (λ)	Calculation	Luminosity (L)	Spectral Type	Ontozone
$H_0$	0.500	$L=\sqrt[-0.4123]{0.500}$	5.372	F1.760	Parahabitable
$H_1$	0.750	$L=\sqrt[-0.4123]{0.750}$	2.009	F7.615	Habitable
$H_2$	0.950	$L=\sqrt[-0.4123]{0.950}$	1.132	G1.043	Hospitable
$H_3$	1.385	$L=\sqrt[-0.4123]{1.385}$	0.454	G7.726	Hospitable
$H_4$	1.770	$L=\sqrt[-0.4123]{1.770}$	0.250	K1.108	Habitable
$H_5$	4.850	$L=\sqrt[-0.4123]{4.850}$	0.022	K9.972	Parahabitable

**Keppy**: Seems like a lot of calculating and converting...

Well, without going into the gory details, you can calculate the relative or Kelvin temperature directly by:

$$K = 5800 (\lambda^{-0.3191})$$
  $T = \lambda^{-0.3191}$ 

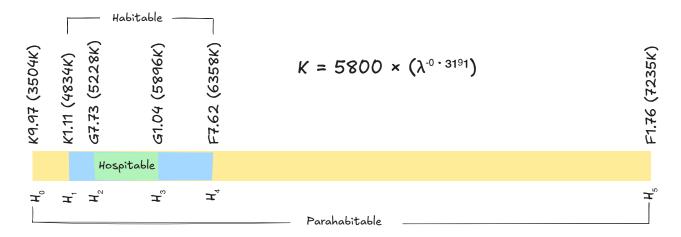
... which will allow you to calculate the spectral type for any perannual orbit at any orbital distance, and the reverse calculations are:

$$\lambda = \sqrt[-0.3191]{rac{K}{5800}}$$
  $\lambda = \sqrt[-0.3191]{T}$ 

... which will give you the orbital distance of the perannual orbit for a star of any given Kelvin temperature (K) or relative temperature (T), since  $T = \frac{K}{5800}$ .

#### Thermal Axis for Perannual Orbits

This diagram shows the stellar surface temperatures (K) and corresponding spectral types required for a star's *perannual orbit* to fall on each thermozone boundary  $H_0$  through  $H_5$ . The core equation relates perannual distance scaling factor  $\lambda$  to stellar temperature K.



## **Orbital Habitability Index (OHI)**

The Orbital Habitability Index (OHI) is a measure of how likely a planet is to be habitable based on its orbit, with the nucleal orbit assumed to be 100% habitable and orbits closer-in and farther-out becoming progressively less habitable. It is calculated using one of two equations, depending on whether the orbit in question is *intranucleal* or *extranucleal*:

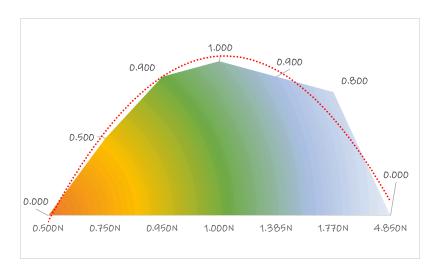
The OHI provides a scalar measure (0.00–1.00) of the *relative biological viability* of a planetary orbit based on its distance from the nucleal orbit  $N=\sqrt{L}$ . It assumes a peak habitability of 1.00 (100%) at 1.000N, declining linearly in each direction.

$$H_I = egin{cases} 2rac{D}{N} - 1 & ext{if } D \leq N \quad ext{(intranucleal)} \ -0.26rac{D}{N} + 1.26 & ext{if } D > N \quad ext{(extranucleal)} \end{cases}$$
 Where  $R = rac{D}{N}: \quad H_I = egin{cases} 2R - 1 & ext{if } R \leq 1 \quad ext{(intranucleal)} \ -0.26R + 1.26 & ext{if } R > 1 \quad ext{(extranucleal)} \end{cases}$ 

#### Where:

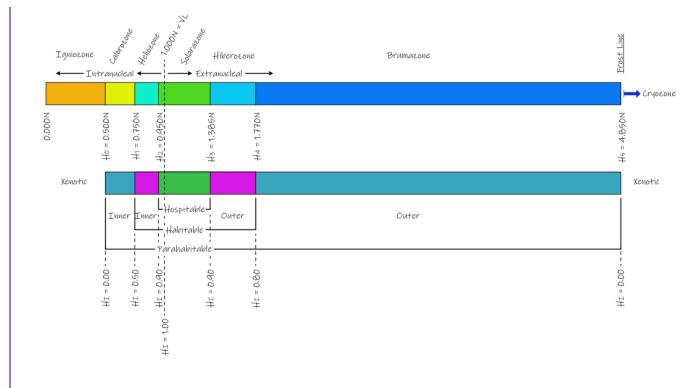
- ullet  $H_I$  = the numeric value of the orbit's habitability index
- D = the orbit's distance in AU
- N = the nucleal orbit's distance in AU

Values of D < 0.500N and > 4.850N return *negative numbers* for  $H_I$ , indicating that the orbit is not hospitable, habitable, or parahabitable for Earth-type lifeforms.



Orbit Type	Orbit Distance	Habitability Index
Intranucleal	0.500N	0.00
Intranucleal	0.750N	0.50
Intranucleal	0.950N	0.90
Nucleal	1.000N	1.00
Extranucleal	1.385N	0.90
Extranucleal	1.770N	0.80
Extranucleal	4.850N	0.00

# **Habitability Axis Plate**



# M002 - Stars — 02 Parameters

# **Stellar Parametrics**

In M002 - Stars — 01 Spectral Classes, we covered spectral classes and spectral types and their association to the surface temperatures of stars. Stars, like planemos, have a basic set of parameters that describe them:

- Temperature How hot is the surface?
  - Absolute measure: Kelvin (K)
  - Relative measure: Solar units (T)
- Mass How much material is there? (M)
- Luminosity How bright is it? (L)
- Radius How big is it? (R)
- Lifetime How long does it shine? (Q)
  - Chiefly relevant to Main Sequence stars, particularly stars that are Solar Cognates (more on this below.)

#### Notes:

- 1. Where we use lower-case letters for the parameters of planemos, we use upper-case letters for stars, so it's easy to tell them apart.
- 2. While **mass** (m) is the primary parameter for planets, with **density** ( $\rho$ ) secondary, for stars **Temperature** (T) is the primary parameter, and **radius** (R) is secondary.

While luminosity is technically derived from a star's temperature and radius (see
the Stefan-Boltzmann Law, below), it plays a central role in modeling stellar
systems — particularly when calculating orbit distances, habitable zones, and
irradiance. In practice, it's often treated as the secondary parameter after
termperature for thesisastics.

# **Equations of State**

A regularized set of empirical relationships can be used to estimate any stellar parameter from the others — assuming a Main Sequence **blackbody**-like star (see <u>Sidebar — What Is The Main Sequence</u>).

Keppy: And a blackbody is...?

Excellent question! A blackbody is an idealized physical object that:

- 1. **Absorbs all** incoming electromagnetic radiation no reflection, no transmission.
- 2. **Emits radiation** purely based on its temperature not its material, shape, or color.
- Emits a perfectly smooth, continuous spectrum (a "thermal spectrum").

A blackbody is the theoretical gold standard for radiant heat emission — a perfect radiator and absorber.

# Why "Blackbody" Matters Here

Most stars (especially Main Sequence stars) behave **approximately like blackbodies**, meaning their energy output can be modeled using **temperature alone**. This makes them excellent candidates for:

- Temperature-based modeling
- Color-temperature mapping (blue = hotter, red = cooler)
- Spectrum-based classification (like spectral classes O–M)
- Real-World Deviation
  - Planets, dust clouds, and even stars aren't *perfect* blackbodies.
  - Real objects have an emissivity ε between 0 and 1:

$$F=arepsilon\sigma T^4$$

But stars are close enough that the blackbody approximation works very well.

**Hippy**: Sorry you asked, Keplarius?

Yes, that's a bit technical and complicated, but it's also extremely *important* to what comes next.

Here are the promised equations:

Temperature (T)	Mass (M)	Radius (R)	Lifetime (Q)
$T=\sqrt[1.98]{M}$	$M=\sqrt[0.9]{R}$	$R=M^{0.9}$	$Q=M^{-2.5}$
$T=\sqrt[1.8]{R}$	$M=T^{1.98}$	$R=T^{1.8}$	$Qpprox{^{-0.36}\!\sqrt{R}}$
$T=Q^{-0.2}$	$M=Q^{-0.4}$	$R=Q^{-0.36}$	$Q=T^{-5}$

#### NOTE:

All of the above equations are *approximations*; stars are a much more variable set of objects (after all, they're mostly gas and plasma, so fluid dynamics plays a major role in their characteristics). These equations work **best** *in general* **for main sequence stars** of all classes.

**Keppy**: You said Luminosity was the second most important parameter for stars, but it doesn't appear in the table...?

Well spotted, Keppy! There's a reason.

#### The Stefan-Boltzmann Law

The Stefan-Boltzmann Law is a formulation that relates the **luminosity** of any luminous object to its **temperature** and **surface area**:

$$L = 4\pi R^2 \sigma T^4$$

Where:

- 4πR² = the surface area of the body
- T = is the temperature of the body in Kelvin
- σ = the Stefan-Boltzmann constant
  - $\sigma = 5.670374419 imes 10^{-8} Wm^{-2}K^{-4}$ 
    - Watts per square meter per Kelvin to the fourth power 1 K<sup>4</sup>
    - It tells you how much radiant energy per second (i.e., power) is emitted by a 1 square meter portion of a perfect blackbody at 1 K<sup>4</sup>.

And this is why we needed the quick aside into the term "blackbody" earlier.

In thesiastics terms, we can simplify the Stefan-Boltzmann equation to:

$$\frac{L_s}{L_{Sun}} = \left(\frac{R_s}{R_{Sun}}\right)^2 \left(\frac{K_s}{K_{Sun}}\right)^4$$

Where:

•  $L_S$  = the absolute luminosity of the star

•  $L_{Sun}$  = the absolute luminosity of the Sun

•  $R_S$  = the absolute radius of the star

•  $R_{Sun}$  = the absolute radius of the Sun

K<sub>S</sub> = the Kelvin temperature of the star

•  $K_{Sun}$  = the Kelvin temperature of the Sun

Because the form  $\frac{X_s}{X_{Sun}}$  is the standard for converting a parameter to solar units, and

 $T=rac{K_s}{K_{Sun}}$  , this equation becomes:

 $L = R^2 T^4$ , with derivations of

$$R=rac{\sqrt{L}}{T^2}, \qquad T=\sqrt[4]{rac{L}{R^2}}$$

## **Parameter Calculation Precedence**

The above being the case, there is a "best" order for calculating stellar parameters when starting from any given parameter (though it is always best start with K or T whenever possible).

All parameters (except K) are expressed in Solar-relative units; that is, T = 10 for 5800 K, R = 10 for the solar radius, etc.

## Starting with Temperature (T) or (K)

Primary dependency chain: T/K  $\rightarrow$  R  $\rightarrow$  L  $\rightarrow$  M  $\rightarrow$  Q

$$T = rac{K}{5800} \quad or \quad K = 5800 T$$
  $R = T^{1.8}$   $L = R^2 T^4$   $M = T^{1.98} \quad or \quad M = \sqrt[0.9]{R}$   $Q = T^{-5} \quad or \quad Q = M^{-2.5}$ 

#### Starting with Mass (M)

Primary dependency chain:  $M \to T/K \to R \to L \to Q$ 

$$T=\sqrt[1.98]{M}$$
  $K=5800T$   $R=T^{1.8}$   $or$   $R=M^{0.9}$   $L=R^2T^4$   $Q=T^{-5}$   $or$   $Q=M^{-2.5}$ 

# Starting with Radius (R)

Primary dependency chain:  $R \to T \to K \to L \to M \to Q$ 

$$T=\sqrt[18]{R} \ K=5800T \ L=R^2T^4 \ M=T^{1.98} \ Q=T^{-5} \quad or \quad Q=M^{-2.5}$$

# Starting With Luminosity (L)

Primary dependency chain:  $L \rightarrow T \rightarrow K \rightarrow R \rightarrow M \rightarrow Q$ 

$$T=\sqrt[7.6]{L} \ K=5800T \ R=T^{1.8} \ M=T^{1.98} \ Q=T^{-5} \ \ or \ \ Q=M^{-2.5}$$

#### Starting with Lifetime (Q)

\*As soon as you assume you'd never want to do this, you'll find a case for doing it.\* **Primary dependency chain**:  $Q \to T \to K \to R \to L \to M$ 

$$T = Q^{-0.2}$$

$$K = 5800T$$

$$R = Q^{-0.36}$$

$$L = R^2T^4$$

$$M = \sqrt[3]{L}$$

# M002 - Stars — 03 The Nucleal Orbit

#### The Nucleal Orbit

The average distance from Earth to the Sun — about  $1.496 \times 10^8$  km — is defined as one **astronomical unit (AU)**. Due to Earth's slightly elliptical orbit, this distance varies by approximately  $\pm 2.5$  million km between Earth's closest approach to and farthest distance from the Sun.

So, for all practical (and thesiastic) purposes the Earth's orbital distance (a) is a = 1.0AU. In fact a is the commonly used symbol for any orbital distance when it is expressed in Astronomical Units.

For our purposes, I have revived an old word from the dusty backroom shelves of English — *nucleal* — and given it new life:

**Nucleal Orbit** (N): the orbital distance from any given star at which a planet receives the same stellar irradiance as Earth receives from the Sun at 1 AU.

... and given it the utterly unimaginative symbol, N.

The important thing to note here is that *N* is not constant, but varies from star to star, and it is calculated by:

$$N = \sqrt{L}$$

Where:

• L = the Luminosity of the star in relative units

Obviously for the Sun:

$$N=\sqrt{L}=\sqrt{1}=1$$

Keppy: So for a dimmer star N shifts closer to the star?

**Hippy**: And for a brighter star, it shifts farther out from the star.

Correct on both counts. And once we know N, we can express the **habitable zone** (details coming!) as a proportional range around it. For instance, for a star of half the Sun's luminosity  $L=0.5\odot$ :

$$N = \sqrt{L} = \sqrt{0.5} = 0.7071~AU$$

#### The Nucleal Orbit and the Habitable Zone

A quick survey of the existing literature reveals a commonly held definition for the **habitable zone** as:

$$\langle 0.950 \wedge 1.385 \rangle N$$

... or, in other words: between 95% of the nucleal orbit distance to 1.385 times (138.5%) the nucleal orbit distance. In the case of our hypothetical  $L=0.5\odot$  star and its N=0.7071~AU nucleal orbit, the range of its habitable zone calculates to:

$$N=0.7071~AU$$
 Inner Edge  $=0.950N=(0.950)(0.7071)=0.6717~AU$  Outer Edge  $=1.385N=(1.385)(0.7071)=0.9793~AU$ 

**Keppy**: So ... the *outer edge* of this star's habitable zone is *closer to its star* than *Earth orbits from the Sun*.....

Exactly. But, this region is only a part of a total star system.

#### The Ontozones - Two Habitable Zones

To start with, some scientist posit a wider, more "optimistic habitable zone" region, covering:

$$\langle 0.750 \wedge 1.770 \rangle N$$

For our purposes, we call this *wider spread* the actual **habitable zone** and we call the narrower span the **hospitable zone**, so that the *hospitable zone* comprises a middle lane between the extremes of the *habitable zone*:

$$\frac{1.385 - 0.95}{1.77 - 0.75} = \frac{0.435}{1.02} = 0.4265 \ AU$$

... about 42.65% of it, in fact.

Orbital Range	Ontozones
⟨0.750 ∧ 0.950⟩N	Habitable Zone
⟨0.950 ∧ 1.385⟩N	Hospitable Zone
⟨1.385 ∧ 1.770⟩N	Habitable Zone

It has also been suggested that "desert" planets (think Dune, Tattooine) might orbit in the zone between  $(0.500 \land 0.750)N$  and we might call this the "desert planet zone", which would be, by definition, **parahabitable** to **habitable** (but mostly the former).

Orbital Range	Ontozones
⟨0.500 ∧ 0.750⟩N	Parahabitable
⟨0.750 ∧ 0.950⟩N	Habitable Zone
⟨0.950 ∧ 1.385⟩N	Hospitable Zone
⟨1.385 ∧ 1.770⟩N	Habitable Zone

# The Frost Line (F)

Research indicates that beyond a distance of about  $a=4.850\ AU$  in our Solar system, water cannot remain liquid due to insufficient irradiance from the Sun. This distance is sometimes termed the "Frost Line" or "Ice Line", and an orbital distance of a=4.850N is the value we set for this outer limit.

#### For instance:

- Mars' orbit in our own Solar system is a=1.524~AU, well within the 1.770N limit
- The asteroid belt is ≈ ⟨2.2 ∧ 3.2⟩AU, beyond 1.77N, but still within the 4.850 AU F limit. This
  region in our Solar system does not host a sizeable planemo (and likely never did), but if
  one were to exist there, it would probably be parahabitable due to the orbital distance from
  the Sun.

This gives us another range of orbits we can add to our accounting:

Orbital Range	Ontozones
⟨0.500 ∧ 0.750⟩N	Parahabitable
⟨0.750 ∧ 0.950⟩N	Habitable Zone
⟨0.950 ∧ 1.385⟩N	Hospitable Zone
⟨1.385 ∧ 1.770⟩N	Habitable Zone
⟨1.770 ∧ 4.850⟩N	Parahabitable

Jupiter's orbit is at  $a=5.204\ AU$ , well *beyond* the  $4.850\ AU$  limit, and things just get colder from there, so we can specify that if any kind of "life" does exist in this region it is likely to be extremophile by Earth standards, which WBN denotes as "*xenotic*".

Orbital Range	Ontozones
⟨0.500 ∧ 0.750⟩N	Parahabitable
⟨0.750 ∧ 0.950⟩N	Habitable Zone
⟨0.950 ∧ 1.385⟩N	Hospitable Zone
⟨1.385 ∧ 1.770⟩N	Habitable Zone
⟨1.770 ∧ 4.850⟩N	Parahabitable
4.850N →	Xenotic

Similarly, any "life" that might come to be on a body orbiting closer than 0.500N would also be xenotic:

Orbital Range	Ontozones
← 0.500N	Xenotic
⟨0.500 ∧ 0.750⟩N	Parahabitable
⟨0.750 ∧ 0.950⟩N	Habitable Zone
⟨0.950 ∧ 1.385⟩N	Hospitable Zone
⟨1.385 ∧ 1.770⟩N	Habitable Zone
⟨1.770 ∧ 4.850⟩N	Parahabitable
4.850N →	Xenotic

Finally, we differentiate between inner and outer zones, and define notations for each:

Orbital Range	Ontozones	Notation
← 0.500N	Inner Xenotic Zone	$Z_{IX}$
⟨0.500 ∧ 0.750⟩N	Inner Parahabitable Zone	$Z_{IP}$
⟨0.750 ∧ 0.950⟩N	Inner Habitable Zone	$Z_{IH}$
⟨0.950 ∧ 1.385⟩N	Hospitable Zone	$Z_H$
⟨1.385 ∧ 1.770⟩N	Outer Habitable Zone	$Z_{OH}$
⟨1.770 ∧ 4.850⟩N	Outer Parahabitable Zone	$Z_{OP}$
4.850N →	Outer Xenotic Zone	$Z_{OX}$

This gives us a full inventory of orbital limits for any star system we choose to devise.

# M002 - Stars — 05 The Perannual Orbit

#### The Perannual Orbit

There is one remaining essential star system orbit, which I have called the **perannual** orbit. The word comes from the Latin *per annum*, meaning "per year" or "each year", and the name reflects that this is the orbit in any star system which has an orbital period (*P*) of exactly one Earth year.

#### **IMPORTANT**

"One Earth Year" in this case is the duration of Earth's complete orbit around the Sun relative to the larger reference frame of the "fixed" stars; thus this is called the **sidereal year**, from the Latin *sidus*, "star". This is measured and denoted in terms of **ephemeris** 

**days** — which are *defined* to be exactly 86400 *seconds* in duration. Thus, the sidereal year (and, consequently, the perannual year) has a duration of:

$$\begin{array}{c} 365.256363004 \quad \text{Ephemeris Days} \\ or \\ 365^d \; 6^h \; 9^m \; 9.763545^s \end{array}$$

This is *not* a "year" as experienced by inhabitants on the surface of a planet on this orbit (that is called the **tropical year**, which is in part dependent upon the *rotational period* of the planet, itself); this is the **sidereal year**.

Please see <u>Sidebar — Units and Measures of Time</u> for a more in-depth discussion of this topic.

We denote the perannual year as *A*, and its location in the star system *is not constant* (the same as the *nucleal orbit* (*N*) but is *determined* by the mass of the star(s), and – to a small but measurable degree – by the mass of the planet.

Please see M002 - Stars — 06 Relating the Nucleal and Perannual Years for an in-depth exploration of this relationship.

The perannual orbit is determined not by the luminosity of the star(s) in the system but by **mass**, mostly of the stars(s), but the mass of the planemo can become a calculatory relevant factor if it is a significant fraction of the mass of the star(s).

The perannual orbit is an *orbital distance*, but it is predicated on the **period** of that orbit — how long it takes the planemo to complete one entire orbit (measured in Earth years). **ANY** planemo orbital period is calculated (in relative terms) by:

$$P=\sqrt{rac{a^3}{M+m}}$$
  $a=\sqrt[3]{P^2(M+m)}$   $M+m=rac{a^3}{P^2}$  Believe it or not, this has its uses

#### Where:

- P = the planemo's orbital period in Earth sidereal years
- a = the measure of the semi-major axis of the planemo's orbit
- *M* = the mass of the star(s) in Solar masses
- m = the mass of the planemo (also expressed in Solar) masses

In many cases (such as that of Earth), *m* is such a small number that it can be ignored without drastically altering the value of *P*. In the case of Earth:

- *M* = 1⊙
- $m=0.000003003\odot$  (3.003 imes  $10^{-6}$ ) three *millionths* of the Sun's mass
- a=1 AU

Calculating with only the Sun's mass:

$$P=\sqrt{rac{a^3}{M}}=\sqrt{rac{1^3}{1}}=\sqrt{rac{1}{1}}=\sqrt{1}=1 ext{ years}$$

Calculating with **both** masses:

$$P = \sqrt{\frac{a^3}{M+m}}$$

$$= \sqrt{\frac{1^3}{1+0.000003003}}$$

$$= \sqrt{\frac{1}{1.000003003}}$$

$$= \sqrt{0.999997}$$

$$P = 0.9999985 \text{ years}$$

... a difference of about 47.384 seconds.

#### **Q** Takeaways:

The *perannual orbit* defines the location in any star system where a planemo would complete one sidereal Earth year.

It may be closer-in than the nucleal orbit (**intranucleal**) or farther out than the nucleal orbit (**extranucleal**).

If it is ever *the same as the nucleal orbit*, then the star(s)' mass(es) must be  $M = 1 \odot$ , and — ideally — the planemo's mass must be  $m = 1 \bigoplus$ .

Unlike the *nucleal orbit* (which depends on *stellar irradiance*), the perannual orbit *depends only the mass of the system* — and serves as a *temporal* rather than *thermal* reference point.

As shown above, the *distance* of any orbit can be calculated from the period and the masses via:

$$a=\sqrt[3]{P^2(M+m)}$$

... but if we already know that P = 1, it drops out of the equation:

$$a=\sqrt[3]{M+m}$$

... such that the distance of the orbit is simply the cube-root of the sum of the masses.

For clarity, we denote the *distance* of the perannual orbit with an *A* (for *anno*), so our equation becomes:

$$A=\sqrt[3]{M+m}$$
 When taking into account both masses  $A=\sqrt[3]{M}$  When using only the central mass

# M002 - Stars — 04 Thermozone Orbits

# **Star System Thermozones**

We've already introduced the term Habitable Zone before, sometimes also prosaically referred to as "The Goldilocks Zone".

Hippy: Silliness!

Well.... Scientists do try to keep things accessible for those not familiar with the official lingo.

Anyway, broadly speaking, this is the range of orbital distances around a given star in which an orbiting planemo might reasonably be expected to retain liquid water and a reasonably dense atmospheric envelope. In the previous section, we defined the *parahabitable*, *habitable*, and *hospitable* zones as occupying this region.

**Keppy**: But this is based on ... what?

I'm glad you asked; it's based on how much energy (irradiance) the planet receives from its star compared to how much insolation the Earth receives from the Sun (you may remember this concept from our discussion of the *nucleal orbit*. And *that* gives us our standard candle (if you'll pardon the pun).

# Naming The Zones And Labeling Their Limits

#### The Thermozones

For ease of remembering these zones and their ontosomic characteristics we use the **thermozone** naming system:

Thermozone	Orbital Range	Ontozones	Notation	
Igniozone	← 0.500N	Inner Xenotic Zone	$Z_{IX}$	"Desert Planet Zone"
Calorozone	⟨0.500 ∧ 0.750⟩ N	Inner Parahabitable Zone	$Z_{IP}$	

Thermozone	Orbital Range	Ontozones	Notation	
Heliozone	$\begin{array}{c} \langle 0.750 \wedge 0.950 \rangle \\ N \end{array}$	Inner Habitable Zone	$Z_{IH}$	
Solarazone	$\begin{array}{c} \langle 0.950 \wedge 1.385 \rangle \\ N \end{array}$	Hospitable Zone	$Z_H$	
Hiberozone	⟨1.385 ∧ 1.770⟩ N	Outer Habitable Zone	$Z_{OH}$	
Brumazone	⟨1.770 ∧ 4.850⟩ N	Outer Parahabitable Zone	$Z_{OP}$	
Cryozone	4.850N →	Outer Xenotic Zone	$Z_{OX}$	"Glacier Planet Zone"

#### These names are derived from:

• Igniozone: Latin ignis, "fire"

• Calorozone: Latin calor, "hot, heat"

Heliozone: Greek Helios, an early name of the Sun god

- Planemos in this region might be somewhat Earth-like in environment, but generally warmer\*
- Solarazone: Latin solar, from Sol, a title of the Sun god
  - Planemos in this region are likely to be very Earth-like in their environment\*

• Hiberozone: Latin hiberno, "cold"

• Brumazone: Latin bruma, "winter"

• Cryozone: Greek kryo, "cold"

#### **Thermozone Limit Notation**

For ease of reference, the limiting orbital distances of the thermozones are denoted by an *H* accompanied by a subscript:

Notation	Orbital Distance
H <sub>o</sub>	0.500N
H <sub>1</sub>	0.750N
H <sub>2</sub>	0.950N
H <sub>3</sub>	1.385N
$H_{_4}$	1.770N

<sup>\*</sup> Assuming they are otherwise Earth-like in size and composition.

Notation	Orbital Distance
H <sub>5</sub>	4.850N

#### Adding these to our earlier table:

Thermozone	Zone Limits	Orbital Range	Ontozones	Notation	
Igniozone	← H <sub>0</sub>	← 0.500N	Inner Xenotic Zone	$Z_{IX}$	"Desert Planet Zone"
Calorozone	$\langle H_0 \wedge H_1 \rangle$	<0.500 ∧ 0.750⟩N	Inner Parahabitable Zone	$Z_{IP}$	
Heliozone	$\langle H_1 \wedge H_2 \rangle$	<0.750 ∧ 0.950⟩N	Inner Habitable Zone	$Z_{IH}$	
Solarazone	$\langle H_2 \wedge H_3 \rangle$	⟨0.950 ∧ 1.385⟩N	Hospitable Zone	$Z_H$	
Hiberozone	$\langle H_3 \wedge H_4 \rangle$	⟨1.385 ∧ 1.770⟩N	Outer Habitable Zone	$Z_{OH}$	
Brumazone	⟨H <sub>4</sub> ∧ H <sub>5</sub> ⟩	⟨1.770 ∧ 4.850⟩N	Outer Parahabitable Zone	$Z_{OP}$	
Cryozone	$H_{5} \rightarrow$	4.850N →	Outer Xenotic Zone	$Z_{OX}$	"Glaci Planet Zone"

This gives us a very robust way of discussing orbital distances in any star system.

Note that the *nucleal orbit*, being always N = 1.0N, always falls within the Solarazone. In fact, it always falls at 11.49% *into* the Solarazone from its inner edge.

# M002 - Stars — 07 Fine-tuning Stellar Parameters Stars — 2.07 Fine-tuning Stellar Parameters Standard Parameter Equations

The Standard Parameter Equations (see M002 - Stars — 02 Parameters):

Temperature (T)	Mass (M)	Radius (R)	Lifetime (Q)
$T=\sqrt[1.98]{M}$	$M=\sqrt[0.9]{R}$	$R=M^{0.9}$	$Q=M^{-2.5}$
$T=\sqrt[1.8]{R}$	$M=T^{1.98}$	$R=T^{1.8}$	$Qpprox{^{-0.36}\!\sqrt{R}}$
$T=Q^{-0.2}$	$M=Q^{-0.4}$	$R=Q^{-0.36}$	$Q=T^{-5}$

*generally* work well for most **Main Sequence** stars, but a survey of known stars in the Solar neighborhood —

Hippy: "Wha-"

... which is too complex and extensive to detail here — suggests that modest adjustments to a couple of key exponents yield parameter equations that better reflect observed stellar characteristics. Since thesiastics prioritizes plausible-world construction over strict theoretical purity, these revised values offer better performance across the mass range of interest.

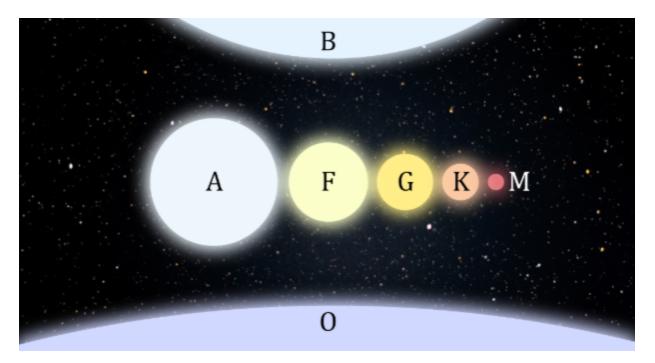
#### **Modified Parameters Table**

Temperature (T)	Mass (M)	Radius (R)	Lifetime (Q)	Luminosity (L)
$T=\sqrt{M}$	$M=\sqrt[0.9]{R}$	$R=M^{0.9}$	$Q=M^{-2.5}$	$L=M^{3.8}$
$T=\sqrt[1.8]{R}$	$M=T^2$	$R=T^{1.8}$	$Qpprox{^{-0.36}\!\sqrt{R}}$	$Lpprox R^{4.ar{2}}$
$T=Q^{-0.2}$	$M=Q^{-0.4}$	$R = Q^{-0.36}$	$Q=T^{-5}$	$L=T^{7.6}$
$T=\sqrt[7.6]{\overline{L}}$	$M=\sqrt[38]{\overline{L}}$	$Rpprox \sqrt[42]{L}$	$Q=L^{-1.52}$	$L=\sqrt[-1.52]{Q}$

#### Notes:

- The parameter relationship that changed from the previous table was  $T\leftrightarrow M$ , where the exponent increased slightly from 1.98 to 2.0
- The major change is the addition of direct calculation for the parameters to-and-from luminosity; these are included for the purpose of simplifying much of the math related to M002 - Stars — 08 `Sun-Like` Stars.
- For greatest accuracy:
  - The exponent 7.6 can be more precisely specified as 7.5778
  - The exponent 3.8 can be more precisely specified as 3.7889

# M002 - Stars — 01 Spectral Classes



# Stars and Spectral Classes: The Fusion-Fueled Continuum

First: The spectral class system used throughout this guide — the sequence **O**, **B**, **A**, **F**, **G**, **K**, **M** — is historically rooted in the observational astronomy of the late 19th and early 20th centuries. Its peculiar alphabetical order reflects the evolution of stellar classification from empirical cataloging to physical understanding.

For readers curious about its origins — including the critical work of **Annie Jump Cannon**, **Cecilia Payne-Gaposchkin**, and the less brilliant men who received most of the credit — see <u>Sidebar: The Spectral System and the Women Who Built It</u>.

Second: The spectral classes used in WBN are based on a **linearized temperature model**. This approach smooths over the irregularities of the traditional system to support clean interpolation, symbolic clarity, and consistent orbital modeling.

If you're curious about the limitations of the classical OBAFGKM system — and why we've chosen to "straighten the curve" — see <u>Sidebar Module: \_Mind the Gap — The</u>

<u>Shortcomings of the Traditional Spectral Scale</u>.

# **Spectral Class Table**

Here are the spectral classes we'll be working with.

Spectral Class	Low Temp. (K)	High Temp. (K)
0	25000	55000
В	10000	25000
Α	7500	10000
F	6000	7500
G	5000	6000
K	3500	5000
M	2400	3500
Brown ↓ Dwarfs ↓		
L	1300	2400
Т	600	1300
Y	300	600

#### Notes:

- Spectral Classes L, T, and Y are "special cases" which are covered in detail in another module (\( \) insert module name here \( \)>
- Each range reflects a star's **surface temperature**, typically noted as  $T_{\rm eff}$  in astronomical literature.
- In WBN:
  - **K** = temperature in Kelvin
  - **T** = temperature *relative to the Sun* (i.e., ⊙ = 5800K ⇒ T = 1.0)

# Spectral Type

Each spectral class is subdivided into 10 spectral types, numbered 0 (hottest) to 9 (coolest).

Hippy: Wait, that's -

Yes, it runs backwards. No, we're not happy about it, either (don't shoot the messenger).

#### For example:

• The Sun, at **5800K**, is classified as a **G2** star —

Spectral Class: G

Spectral Type: 2

#### **Note on Spectral Type Precision in WBN**

In this system, a **spectral type** is defined by its **numerical position** within a spectral class. For example:

- G2, G2.3, and G2.9 are all Type 2
- The decimal simply adds interpolation precision it does not define a new type.
- Therefore, **Type 2** refers to the full range ⟨2.0 ∧ 2.999····⟩ within class *G*.

This allows for relatively simple mathematical treatment of the relationship between spectral type (T) and surface temperature (K).

$$\mathcal{Z} = \frac{\kappa - K}{p}$$

$$\kappa = \mathcal{E} b + K$$

$$K=\kappa-\mathcal{E} p$$

$$b = \frac{\kappa - K}{2}$$

Where:

- K = the star's surface temperature in Kelvin
- κ = the upper bound temperature of the relevant spectral class
- b = the thermal interval constant for the relevant spectral class
- S = the spectral type number

#### The Thermal Interval Constant (b)

Where does p come from?

For a given spectral class b can be calculated by:

$$p = \frac{high\ temp - low\ temp}{10}$$

Here is the above table with these constants added:

Spectral Class	Low Temp. (Kelvin)	High Temp. (Kelvin)	Thermal Interval Constant (þ)
Ο	25000	55000	3000

Spectral Class	Low Temp. (Kelvin)	High Temp. (Kelvin)	Thermal Interval Constant (þ)
В	10000	25000	1500
Α	7500	10000	250
F	6000	7500	150
G	5000	6000	100
K	3500	5000	150
М	2400	3500	110
L	1300	2400	110
Т	600	1300	70
Y	300	600	30

# **Example**

Let's run the numbers for the Sun

- Known surface temperature: 5800K
- Checking the table, 5800K falls between 5000K and 6000K, so the Sun is spectral class G
- The high temperature (κ) for spectral class G is κ 6000K
- The thermal interval constant ( $\flat$ ) for spectral class G is  $\flat$  = 100
- What is the Sun's spectral type (2)
   Running the numbers:

$$\mathcal{Z}=rac{\kappa-K}{p}$$
  $\mathcal{Z}=rac{6000-5800}{100}$   $\mathcal{Z}=rac{200}{100}$   $\mathcal{Z}=2$   $\checkmark$ 

The Sun is spectral type G2.

#### Reversing the process:

- The known spectral class of the Sun is G
- The known spectral type of the Sun is 2 = 2
- The high temperature (κ) for spectral class G is κ 6000K

- The thermal interval constant (b) for spectral class G is b = 100
- What is the Sun's Kelvin temperature (K)
   Running the numbers:

$$K = \kappa - 2 p$$
  
 $K = 6000 - (2)(100)$   
 $K = 6000 - 200$   
 $K = 5800 \checkmark$ 

The surface temperature of the Sun is 5800K.

# Converting Between Absolute Kelvin (K) And Solar Relative (T)

Nothing could be simpler:

$$T = \frac{K}{5800}$$

$$K = 5800T$$

For instance: the Sun's surface temperature is K = 5800:

$$T = \frac{K}{5800} = \frac{5800}{5800} = 1 \checkmark$$

Conversely, the Sun's relative temperature is T = 1.0:

$$K = 5800T = (5800)(1) = 5800 \checkmark$$

# **Fictional Examples**

Let's say we have a star called Essem that we want to be spectral type *F3.65*. What is its Kelvin temperature?

- The surface temperature for spectral class F is  $K \in \langle 6000 \land 7500 \rangle$ .
- The thermal interval constant for spectral class F is β = 150.
   Working through the equation:

$$K = \kappa - 2h$$
  
 $K = 7500 - (3.65)(150)$   
 $K = 7500 - 547.5$   
 $K = 6952.5 \checkmark$ 

What is Essem's relative surface temperature?

$$T = \frac{K}{5800}$$

$$T=rac{6952.5}{5800}$$

$$T=1.199$$
  $\checkmark$ 

Essem's relative temperature is  $T = 1.199 \odot$ .

#### **Working The Other Direction**

Let us say that Essem has a near neighbor, Essel, and we know that its relative temperature is  $T = 0.876 \odot$ . What is its spectral type?

First, convert T to K by:

$$K = 5800T = (5800)(0.876) = 5080.8 \checkmark$$

Looking at our table we see that this value falls in spectral class G:

Spectral Class	Low Temp. (Kelvin)	High Temp. (Kelvin)	Thermal Interval Constant (þ)
G	5000	6000	100

... which gives us all the other information we need:

- G-class high temperature is  $\kappa = 6000$
- G-class thermal interval constant is b = 100

The spectral type is:

$$\mathcal{E} = \frac{\kappa - K}{p}$$

$$\mathcal{Z} = \frac{6000 - 5080.8}{100}$$

$$\mathcal{Z} = \frac{919.2}{100}$$

$$\mathcal{Z}=9.192$$
  $\checkmark$ 

Essel's spectral type is *G9.192*.

# **Parameter Ranges By Spectral Class**

	SC →	0	В	Α	F	G	K	M
	High	55000	25000	10000	7500	6000	5000	3500
Kelvin	Mean	40000	17500	8750	6750	5500	4250	2950
	Low	25000	10000	7500	6000	5000	3500	2400
	TIC¹ ( <i>þ</i> )	3000	1500	250	150	100	150	110
	High	9.4828	4.3103	1.7241	1.2931	1.0345	0.8621	0.6034
T⊙	Mean	6.8966	3.0172	1.5086	1.1638	0.9483	0.7328	0.5086
	Low	4.3103	1.7241	1.2931	1.0345	0.8621	0.6034	0.4138
	High	17.0690	7.7586	3.1034	2.3276	1.8621	1.5517	1.0862
R⊙	Mean	12.4138	5.4310	2.7155	2.0948	1.7069	1.3190	0.9155
	Low	7.7586	3.1034	2.3276	1.8621	1.5517	1.0862	0.7448
	High	2.356 M	20.779 k	85.1093	15.1476	3.9709	1.3298	0.1565
L⊙	Mean	348.608 k	2.445 k	38.1967	8.0501	2.3559	0.5015	0.0561
	Low	20.779 k	85.109	15.1476	3.9709	1.3298	0.1565	0.0163
	High	18.7759	8.5345	3.4138	2.5603	2.0483	1.7069	1.1948
M⊙	Mean	13.6552	5.9741	2.9871	2.3043	1.8776	1.4509	1.0071
	Low	8.5345	3.4138	2.5603	2.0483	1.7069	1.1948	0.8193
	High	64.10E- 06	4.00E-03	0.1280	0.4684	1.3041	4.7336	29.3785
Qo	Mean	0.67E-03	65.64E- 03	0.2766	0.8441	2.1003	12.4968	82.4297
	Low	0.69E-06	35.57E- 06	3.47E- 03	0.0146	0.0447	0.1112	0.6614

<sup>&</sup>lt;sup>1</sup> Thermal Interval Constant

# M002 - Stars — 09 Adding Orbits to the System Fleshing Out A Star System

We've established spectral classes and types, thermozones, ontozones, habitability indices, and the two critical orbital distances, *nucleal* (*N*) and *perannual* (*A*).

But planemos don't orbit only at these discreet distances – they're all over the place. Here's a breakdown of our own Solar system's planetary orbit data:

Planet	α (AU)	€	Ontozone
Mercury	0.387	0.2056	Igniozone
Venus	0.723	0.0068	Calorozone
Earth	1.000	0.0167	Solarazone
Mars	1.524	0.0934	Hiberozone
Asteroids	$\langle 2.2 \wedge 3.2 \rangle$ ; $\mu = 2.7$	$\mu = 0.15$	Brumazone
Jupiter	5.204	0.0489	Cryozone
Saturn	9.583	0.0565	Cryozone
Uranus	19.191	0.0472	Cryozone
Neptune	30.070	0.0087	Cryozone

# **Orbital Parameters**

Ignoring the asteroid belt for the moment and inserting Ceres as the largest member of the belt:

Planet	α (AU)	€	Gap¹ (AU)	Interval <sup>2</sup> (AU)
Mercury	0.387	0.2056		
Venus	0.723	0.0067	0.3362	1.8686
Earth	1.000	0.0167	0.2767	1.3825
Mars	1.524	0.0934	0.5237	1.5237
Ceres	2.700	0.1500	0.1763	1.7720
Jupiter	5.204	0.0489	2.5038	1.9273
Saturn	9.583	0.0565	4.3788	1.8415
Uranus	19.191	0.04727	9.6087	2.0027
Neptune	30.070	0.0088	10.8787	1.5669

Notes:

1. The orbital **gap** is calculated by subtracting the planet's orbital distance from the next closer-in planet's orbital distance

$$G = O_n - O_{n-1}$$

>2. The orbital **interval** is calculated by dividing the planet's orbital distance by the next closer-in planet's orbital distance:

$$I = \frac{O_n}{O_{n-1}}$$

What we are concerned with is the *orbital intervals* 

- The minimum interval is between Venus and Earth:  $I=1.3825 \ AU$
- The maximum interval is between Uranus and Neptune:  $I=2.0027\ AU$
- The average interval is  $I \approx 1.74~AU$
- The median interval is  $I \approx 1.81~AU$
- The standard deviation is  $\sigma = 0.2051$ 
  - This gives a 1-σ range of (1.531 ∧ 1.941) AU

This supports defining a WBN-standard orbital interval range of:

<1.500 \( \times 2.000 \) AU
for most planetary system layouts not dominated by resonance or migration effects.</li>

# **Calculating Other Orbits**

This brings us to methods of calculating other orbits in a star system. In practice, any method the thesiast chooses is *valid*, including just putting planemos where "it feels right"; however, even using this method *should* ideally take into account the above statistics and try to avoid an orbital interval between a given planemo and its nearest neighbor of  $< 1.500 \ AU$  or  $> 2.000 \ AU$ .

# **Starting From A Known Orbit**

Most of the time, you'll have pre-established a particular orbit — usually either the *nucleal* or the *perannual* orbit, and want to arrange other planemos in the system relative to that orbit. Notating this orbit as the **base** orbit, we can set up two processes for calculating orbits inferior to (closer-in than) and superior to (farther-out than) that orbit.

#### **Intrabasal Orbit Calculation Process**

$$r_i = B; \; \Omega = ext{ iny $:$} \qquad r_{i-1} = rac{r_i}{\langle \langle \min \wedge \max 
angle 
angle} \quad ext{while $r_{i-1} \geq \Omega$}$$

#### **Extrabasal Orbit Calculation Process**

Where:

- B = basal orbital radius (e.g. the nucleal orbit N)
- $\Omega$  = orbital distance cuttoff (minimum or maximum allowed orbit based on the star system constraints)

# **Usage Strategy**

Assuming the standard interval range  $I \in \langle\langle 1.500 \land 2.000 \rangle\rangle$  AU:

The **intrabasal** and **extrabasal** forms can be used independently depending on your desired anchoring strategy:

#### **Inward-Only Generation**

If you begin at the **basal orbit** (innermost, nucleal, perannual, etc.), use the **intrabasal** form to expand inward via divisive steps:

$$r_0 = B; \; \Omega = ext{ iny $:$} \quad r_{i-1} = rac{r_i}{\langle\langle 1.500 \wedge 2.000
angle
angle}, ext{ while } r_{i-1} \geq \Omega$$

Where:

•  $\Omega$  = the minimum safe orbital distance — usually taken to be a=0.100~AU.

#### **Outward-Only Generation**

If you begin at the **innermost permissible orbit** (e.g. a thermal, Roche, or design constraint), use the **intrabasal** form to expand outward via multiplicative steps:

$$r_0 = B; \; \Omega = ext{ iny }: \quad r_{i+1} = r_i \cdot \langle \langle 1.500 \wedge 2.000 
angle 
angle, \; ext{while } r_{i+1} \leq \Omega$$

Where:

•  $\Omega$  = the farthest orbit desired for a planemo in the system — based on whatever criterion desired, but physically limited to the Hill Sphere radius of the central mass.

Applying these methods can fully define a system.

- If one wanted to start with the innermost safe orbit; e.g.  $B=0.100\ AU$ , then one would use only the extrabasal process to calculate orbits outward.
- Conversely if one wanted to start with the most distant orbit, then one would use only the intrabasal process to calculate orbits inward.

#### **IMPORTANT**

If not starting from the perannual or nucleal orbit, always check randomized orbits

against either (or both) to ensure proper interval gaps fall to either side of that orbit, and adjust accordingly!

# **Worked Example**

Let us say we've identified our nucleal orbit (N) as  $N=0.834\ AU$ , and we want to calculate orbits interior-to and exterior-to that orbit, and we've chosen  $a=0.100\ AU$  as our innermost safe orbit.

## **Working Inward**

$$r_0 = 0.834; \; \Omega = 0.100: \quad r_{i-1} = \frac{r_i}{\langle \langle 1.500 \wedge 2.000 \rangle \rangle}, \; \text{while} \; r_{i-1} \geq 0.100$$
 
$$r_{i-1} = \frac{0.834}{1.723} = 0.482 \; AU \qquad 1.732 := \text{Randomized interval between } \langle 1.500 \wedge 2.000 \rangle \; \text{AU}$$
 
$$r_{i-1} = \frac{0.482}{1.616} = 0.298 \; AU \qquad 1.616 := \text{Randomized interval between } \langle 1.500 \wedge 2.000 \rangle \; \text{AU}$$
 
$$r_{i-1} = \frac{0.298}{1.573} = 0.190 \; AU \qquad 1.573 := \text{Randomized interval between } \langle 1.500 \wedge 2.000 \rangle \; \text{AU}$$
 
$$r_{i-1} = \frac{0.190}{1.884} = 0.101 \; AU \qquad 1.884 := \text{Randomized interval between } \langle 1.500 \wedge 2.000 \rangle \; \text{AU}$$
 
$$r_{i-1} = \frac{0.101}{1.963} = 0.051 \; AU \qquad 1.963 := \text{Randomized interval between } \langle 1.500 \wedge 2.000 \rangle \; \text{AU}$$

We stop at the fourth randomized orbit, because the next orbit randomly generated fails the  $r \geq 0.100~AU$  test.

We now have a system of five orbits:

Orbit	Distance
1	0.101
2	0.190
3	0.298
4	0.482
5 (N)	0.834

We could stop here and have a fully legitimate star system, but let's say we want extranucleal orbits, as well. Again, beginning with the nucleal orbit B=0.834~AU, and setting an outermost orbit of  $\Omega=35.0~AU$ :

$$r_0 = 0.834; \; \Omega = 35.0: \quad r_{i+1} = r_i \cdot \langle \langle 1.500 \wedge 2.000 
angle 
angle, \; ext{while } r_{i+1} \leq 35.0$$

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 $1.829 := Randomized interval between \langle 1.500 \wedge 2.000 \rangle AU$  $r_{i+1} = 0.834(1.829) = 1.525 \; AU$  $r_{i+1} = 1.525(1.969) = 3.003 \; AU$  $1.969 := \text{Randomized interval between } \langle 1.500 \wedge 2.000 \rangle \text{ AU}$  $r_{i+1} = 3.003(1.578) = 4.739 \; AU$  $1.578 := \text{Randomized interval between } \langle 1.500 \wedge 2.000 \rangle \text{ AU}$  $r_{i+1} = 4.739(1.547) = 7.332 \; AU$  $1.547 := \text{Randomized interval between } \langle 1.500 \wedge 2.000 \rangle \text{ AU}$  $r_{i+1} = 7.332(1.552) = 11.379 \ AU$  $1.552 := \text{Randomized interval between } \langle 1.500 \wedge 2.000 \rangle \text{ AU}$  $r_{i+1} = 11.379(1.608) = 18.298 \; AU$  $1.608 := \text{Randomized interval between } \langle 1.500 \wedge 2.000 \rangle \text{ AU}$  $r_{i+1} = 18.298(1.823) = 33.357 \; AU$  $1.823 := \text{Randomized interval between } \langle 1.500 \wedge 2.000 \rangle \text{ AU}$  $r_{i+1} = 33.357(1.778) = 59.309 \ AU$  $1.778 := \text{Randomized interval between } \langle 1.500 \wedge 2.000 \rangle \text{ AU}$ 

We stop at the seventh iteration, as the next value exceeds  $\Omega = 35.0~AU$ .

This expands our system to 11 orbits:

Orbit	Distance
1	0.101
2	0.190
3	0.298
4	0.482
5 ( <i>N</i> )	0.834
6	1.525
7	3.003
8	4.739
9	11.379
10	18.298
11	33.357

... and we can proceed to design planets for each orbit, or eliminate some orbits and install asteroid belts, or adjust orbital intervals to suit our needs.... the sky's the limit.

Hippy: Oh, ha-ha...

C'mon, you had to know I'd use that pun at some point didn't you?

With this method, a thesiast can quickly generate a full planetary system that is physically plausible, statistically grounded, and symbolically consistent with WBN cosmology.

# M002 - Stars — 10 Folding In The Zones

# **Calculating the Thermozones**

Since we know our nucleal orbit is  $N=0.834\ AU$ , we can calculate the thermozone limits:

$$\begin{split} H_0 &= 0.500N = 0.500(0.834) = 0.417 \; AU \\ H_1 &= 0.750N = 0.750(0.834) = 0.626 \; AU \\ H_2 &= 0.950N = 0.950(0.834) = 0.792 \; AU \\ H_3 &= 1.385N = 1.385(0.834) = 1.115 \; AU \\ H_4 &= 1.770N = 1.770(0.834) = 1.476 \; AU \\ H_5 &= 4.850N = 4.850(0.834) = 4.045 \; AU \quad \text{Frost Line} \end{split}$$

And we can add these to our orbits table from above and determine the thermozones and ontozones of the orbits:

Orbit	Distance	Thermozone	Ontozone
1	0.101	Igniozone	Xenotic
2	0.190	Igniozone	Xenotic
3	0.298	Ignoizone	Xenotic
$H_0$	0.417		
4	0.482	Calorozone	Inner Parahabitable
$H_1$	0.626		
$H_2$	0.792		
5 (N)	0.834	Solarazone	Hospitable
$H_3$	1.115		
$H_4$	1.476		
6	1.525	Brumazone	Outer Parahabitable
7	3.003	Brumazone	Outer Parahabitable
$H_5$	4.045		
8	4.739	Cryozone	Xenotic
9	11.379	Cryozone	Xenotic
10	18.298	Cryozone	Xenotic
11	33.357	Cryozone	Xenotic

And, we can calculate the perannual orbital distance and the star's spectral type by:

#### **Perannual Orbit**

0.01 - Introduction

$$L=N^2=0.834^2=0.696 \ M=\sqrt[3.8]{L}=\sqrt[3.8]{0.696}=0.909 \ A=\sqrt[3]{0.909}=0.969 \ AU \ \checkmark$$

The perannual orbit in this system is at A=0.969~AU.

#### Spectral Type

$$L=0.696$$
  $T=\sqrt[7.6]{L}=\sqrt[7.6]{0.696}=0.953\odot$   $K=5800T=5800(0.953)=5529.92$  Spectral Class G:  $lpha=6000;$   $eta=100$ 

$$\mathcal{Z} = rac{\kappa - K}{100} = rac{6000 - 5529.92}{100} = rac{470.08}{100} = 4.701$$

The spectral type of our star is G4.701.

Hippy: Uh..... that perannual orbit distance....

Excellent catch!

Keppy: What ....?

Check this out: we already know that our nucleal orbit is at  $N=0.834\ AU$ . If we put planet on the perannual orbit at  $A=0.969\ AU$  the interval between the nucleal orbit and the perannual orbit is only:

$$I = \frac{0.969}{0.834} = 1.162 \ AU \ \checkmark$$

 $\dots$  which is less than our specified minimum  $I>1.500\ AU.$ 

Keppy: Which means....

**Hippy**: Either we don't have a planet on the nucleal orbit, *or* we don't have a planet on the perannual orbit; those orbits are fixed by the stellar parameters – neither can be shifte.

EXACTLY! This is the power — but also the limitation — of our system. Some things we can tweak as we please; other things we have to work with, or work around.

In this case, we're forced to choose between a planet with Earth's stellar flux, or a planet with Earth's orbital period, but we can't have both.

**Keppy**: What if we drop the nucleal planet and go with the parahabitable planet?

Excellent thought... let's work that through. Here's a modified orbit table taking that into account:

Orbit	Distance	Thermozone	Ontozone	Interval
1	0.101	Igniozone	Xenotic	
2	0.190	Igniozone	Xenotic	1.884
3	0.298	Ignoizone	Xenotic	1.573
$H_0$	0.417			
4	0.482	Calorozone	Inner Parahabitable	1.616
$H_1$	0.626			
$H_2$	0.792			
5 (A)	0.969	Solarazone	Hospitable	»1.927«
$H_3$	1.115			
$H_4$	1.476			
6	1.525	Brumazone	Outer Parahabitable	»1.574«
7	3.003	Brumazone	Outer Parahabitable	
$H_{5}$	4.045			
8	4.739	Cryozone	Xenotic	1.552
9	11.379	Cryozone	Xenotic	1.608
10	18.298	Cryozone	Xenotic	1.823
11	33.357	Cryozone	Xenotic	1.778

The interval between the perannual orbit and the next closer-in orbit is:

$$I = \frac{0.969}{0.482} = 1.927 \; AU$$

... just within our I=2.000~AU maximum, and the interval to the next orbit out is:

$$I = rac{1.525}{0.969} = 1.574 \; AU$$

 $\dots$  which, again, is *just* within our specified minimum I=1.500~AU, so, yes we can drop the nucleal planet and go with the perannual planet, instead.

**Hippy**: I am compelled to point out that the maximum interval is not nearly as absolute as the minimum interval...

Good point! Planemos can certainly have wider intervals between their orbits than  $I=2.000\ AU$  – we just never want them to have an interval *less-than*  $I=1.500\ AU$ .

**Keppy**: But the perannual planet is farther out than the nucleal orbit, so won't it get less stellar flux?

Well spotted! And we can calculate that! Since  $A=0.969\ AU$  and  $N=0.834\ AU$ , and we know that the stellar flux at N=1.0, we can calculate that A is:

$$\Delta = rac{0.969}{0.834} = 1.162$$

... the perannual orbit is  $1.162 \times$  farther out than the nucleal orbit, and since intensity decreases with the square of the distance:

$$F = \frac{1}{\Lambda^2}$$

... we can calculate that the perannual planet receives:

$$F = \frac{1}{1.162^2} = \frac{1}{1.350} = 0.741$$

... about 74.1% of the stellar flux as the nucleal orbit does... but that's still:

$$H_I = -0.26 rac{D}{N} + 1.26 = -0.26 rac{0.969}{0.834} + 1.26 = -0.26 (1.162) + 1.26 = -0.302 + 1.26 = 0.958$$

... an orbital habitability index of 95.8% that of the nucleal orbit. Slightly cooler, but not drastically so.

# M002 - Stars — 08 'Sun-Like' Stars

# Solar Analogs, Cognates, and Twins

The published literature often speaks of "solar analog" stars, but tends to be distressingly vague about exactly what the term means. Generally speaking, it means "a star very much like the Sun".

Keppy: And that doesn't help at all — that could mean any star, really.

You're right; so, for our purposes we have our own definitions, based on *orbits* and the ontozones. But, first, a survey of existing terminology.

# **Existing Definitions**

A "Sun-like star" is a broad term used to describe stars that share characteristics with our own Sun. Astronomers often categorize them into a hierarchy based on their *physical* similarity to the Sun. They all need to be main-sequence stars\*\*, actively fusing hydrogen into helium in their core, like our Sun. Otherwise:

**Solar-type Stars:** This is the broadest category. These stars are broadly similar to the Sun in mass and evolutionary state. Key characteristics include:

• Spectral type: Typically F8V (6300 K) to K2V (4700 K) — more on this below.

**Solar Analogs:** These stars are more similar to the Sun than general solar-type stars, conforming to stricter criteria:

• **Temperature:** Within approximately 500 Kelvin (K) of the Sun's temperature (which is about 5800 K) — between 5300 K (G7V) and 6300 K (F8V).

**Solar Twins:** This is the most restrictive category, for stars that are nearly identical to the Sun. The idea is that they are virtually indistinguishable from our Sun in as many ways as possible:

#### Temperature:

- Within a very narrow range, typically ±10 K of the Sun's temperature 5790 K
   (G2.1V) to 5810 K (G1.9V).
- Some definitions are even stricter, within ±5 K 5795 K (G2.05V) to 5805 K (G1.95V).

#### Age:

- **4.3 4.7 Gyr** (The Sun's age ±200 Ma)
- Sometimes as tight as ±100 Ma, i.e., 4.4 4.6 Gyr

# A Proposed, Clearer System

For thesiastic purposes, our criteria need to be more related to the *habitability* of orbiting planemos than directly to physical similarity between stars. Therefore, WBN defines the following:

#### Solar Analogs:

• Stars whose *perannual orbits* fall within  $\langle 0.500, 4.850 \rangle$  AU, spanning from the Inner Parahabitable Zone to the Outer Parahabitable Zone (H<sub>0</sub> – H<sub>5</sub>).

#### Solar Cognates:

• Stars whose *perannual orbits* fall within  $\langle 0.750, 1.770 \rangle$  AU, spanning from the Inner Habitable Zone to the Outer Habitable Zone (H<sub>1</sub> – H<sub>4</sub>).

#### Solar Twins:

• Stars whose *perannual orbits* fall within  $\langle 0.950, 1.385 \rangle$  AU, spanning the Hospitable Zone  $(H_2 - H_3)$ .

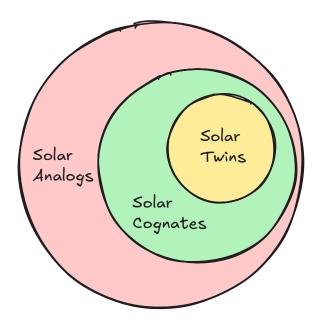
Thus:

- All Solar Twins are also Solar Cognates and Solar Analogs.
- All Solar Cognates are also Solar Analogs.
- Solar Analogs encompass the Solar Cognate and Solar Twin categories.

#### NOTE:

 This perannual-orbit-based requirement is largely arbitrary, predicated on the thesiastic idea that a planemo that is least different from Earth would have an orbital period the same as Earth's.

#### **Nested Ontozonal Categories of Sun-like Stars**



# **Calculating The Spectral Types**

Previously, in M002 - Stars — 06 Relating the Nucleal and Perannual Years, we established that the *distance* of the perannual orbit can be approximated by:

$$A=\sqrt[3]{M}$$

... and in M002 - Stars — 07 Fine-tuning Stellar Parameters, we established the relationship:

$$L = M^{3.8}$$

... which lets us calculate that:

$$A=\sqrt[3]{\sqrt[3.8]{L}}=\sqrt[11.4]{L}$$

In M002 - Stars — 04 Thermozone Orbits, we established that the thermozone limits are calculated by applying fixed scaling factors to the **nucleal orbit distance** (*N*), which is calculated from the square-root of the luminosity:

Limiting Orbit	Calculation
$H_0$	$0.500\sqrt{L}$
$H_1$	$0.750\sqrt{L}$
$H_2$	$0.950\sqrt{L}$
$H_3$	$1.385\sqrt{L}$
$H_4$	$1.770\sqrt{L}$
$H_5$	$4.850\sqrt{L}$

This means that we can set:

$$A=\sqrt[114]{L} \quad ext{equal to} \quad A=0.500\sqrt{L}$$

... and solve for L:

Converting luminosity to temperature:

$$T=\sqrt[7.6]{L}=\sqrt[7.6]{5.372}=1.248~\odot$$

In  $\underline{\text{M002 - Stars}}$  — 02 Parameters, we established the following relationship between solar-unit temperature (T) and Kelvin temperature (K)

$$K = 5800T$$

So, our star has a Kelvin temperature of:

$$K = 5800T = 5800(1.248) = 7235.97 K$$

... and we can calculate the spectral class and type:

$$\mathcal{Z} = \frac{\kappa - K}{b}$$

Where:

- K = the star's surface temperature in Kelvin
- κ = the *upper bound* temperature of the relevant spectral class
- b = the thermal interval constant for the relevant spectral class
- 2 = the spectral *type* number

Taken from the table:

Spectral Class	High Temp. (K)	Thermal Interval Constant (þ)
0	55000	3000
В	25000	1500
Α	10000	250
F	7500	150
G	6000	100
K	5000	150
М	3500	110
L	2400	110
Т	1300	70
Y	600	30

Our Kelvin temperature is 7235.97~K which is an F-type star, so

- $\kappa = 7500$
- b = 150

$$\mathcal{Z} = \frac{\kappa - K}{p} = \frac{7500 - 7235.97}{150} = \frac{264.03}{150} = 1.76$$

So the spectral type of a star with a perannual orbit at 0.500 AU is F 1.76 ✓.

# **Generalizing The Equation**

This logic can be extended for any  $H_{\scriptscriptstyle X}$  value:

By generalizing the scaling factor  $\lambda$ , we can calculate the relative stellar luminosity for **any** perannual orbit distance:

$$0.01$$
 - Introduction  $11.4\sqrt{L} = \lambda\sqrt{L}$   $\lambda = \frac{11.4\sqrt{L}}{\sqrt{L}}$   $\lambda = \frac{11.4\sqrt{L}}{\sqrt{L}}$   $\lambda = L^{\frac{1}{11.4} - \frac{1}{2}}$   $\lambda = L^{\frac{2}{22.8} - \frac{11.4}{22.8}} = L^{-\frac{9.4}{22.8}}$   $\lambda = L^{-0.4123}$   $\therefore L = \frac{-0.4123}{\sqrt[3]{\lambda}}$ 

## A Final Determination

Substituting all of the  $H_x$  values in for  $\lambda$ :

Limiting Orbit	Scaling Factor (λ)	Calculation	Luminosity (L)	Spectral Type	Ontozone
$H_0$	0.500	$L=\sqrt[-0.4123]{0.500}$	5.372	F1.760	Parahabitable
$H_1$	0.750	$L=\sqrt[-0.4123]{0.750}$	2.009	F7.615	Habitable
$H_2$	0.950	$L=\sqrt[-0.4123]{0.950}$	1.132	G1.043	Hospitable
$H_3$	1.385	$L=\sqrt[-0.4123]{1.385}$	0.454	G7.726	Hospitable
$H_4$	1.770	$L=\sqrt[-0.4123]{1.770}$	0.250	K1.108	Habitable
$H_5$	4.850	$L=\sqrt[-0.4123]{4.850}$	0.022	K9.972	Parahabitable

**Keppy**: Seems like a lot of calculating and converting...

Well, without going into the gory details, you can calculate the relative or Kelvin temperature directly by:

$$K = 5800 (\lambda^{-0.3191})$$
  $T = \lambda^{-0.3191}$ 

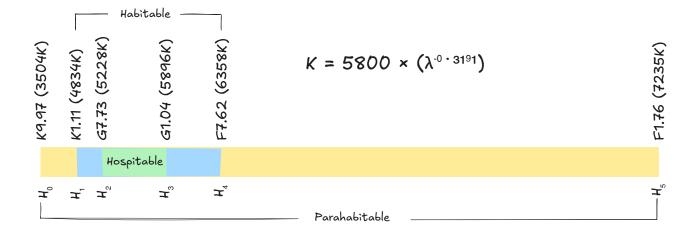
... which will allow you to calculate the spectral type for any perannual orbit at any orbital distance, and the reverse calculations are:

$$\lambda=\sqrt[-0.3191]{K\over 5800} 
onumber \ \lambda=\sqrt[-0.3191]{T}$$

... which will give you the orbital distance of the perannual orbit for a star of any given Kelvin temperature (K) or relative temperature (T), since  $T = \frac{K}{5800}$ .

#### **Thermal Axis for Perannual Orbits**

This diagram shows the stellar surface temperatures (K) and corresponding spectral types required for a star's *perannual orbit* to fall on each thermozone boundary  $H_0$  through  $H_5$ . The core equation relates perannual distance scaling factor  $\lambda$  to stellar temperature K.



#### **Orbital Habitability Index (OHI)**

The Orbital Habitability Index (OHI) is a measure of how likely a planet is to be habitable based on its orbit, with the nucleal orbit assumed to be 100% habitable and orbits closer-in and farther-out becoming progressively less habitable. It is calculated using one of two equations, depending on whether the orbit in question is *intranucleal* or *extranucleal*:

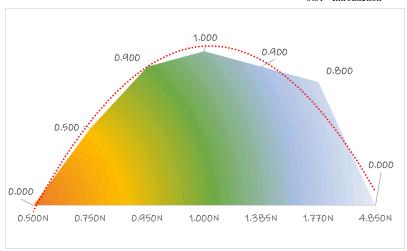
The OHI provides a scalar measure (0.00–1.00) of the *relative biological viability* of a planetary orbit based on its distance from the nucleal orbit  $N = \sqrt{L}$ . It assumes a peak habitability of 1.00 (100%) at 1.000N, declining linearly in each direction.

$$H_I = \left\{ egin{array}{ll} 2rac{D}{N} - 1 & ext{if } D \leq N \quad ext{(intranucleal)} \\ -0.26rac{D}{N} + 1.26 & ext{if } D > N \quad ext{(extranucleal)} \end{array} 
ight.$$
 Where  $R = rac{D}{N}: \quad H_I = \left\{ egin{array}{ll} 2R - 1 & ext{if } R \leq 1 \quad ext{(intranucleal)} \\ -0.26R + 1.26 & ext{if } R > 1 \quad ext{(extranucleal)} \end{array} 
ight.$ 

#### Where:

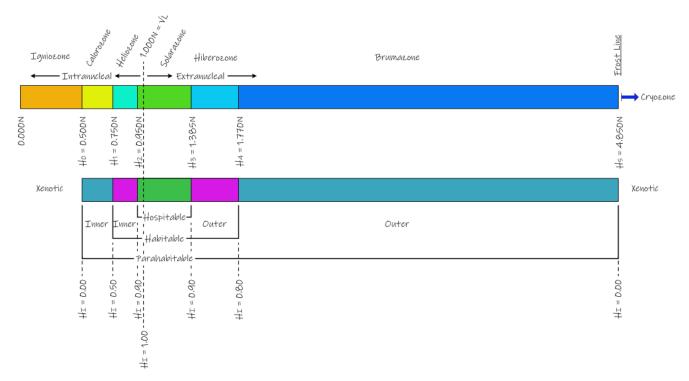
- $H_I$  = the numeric value of the orbit's habitability index
- D = the orbit's distance in AU
- N = the nucleal orbit's distance in AU

Values of D < 0.500N and > 4.850N return *negative numbers* for  $H_I$ , indicating that the orbit is not hospitable, habitable, or parahabitable for Earth-type lifeforms.



Orbit Type	Orbit Distance	Habitability Index
Intranucleal	0.500N	0.00
Intranucleal	0.750N	0.50
Intranucleal	0.950N	0.90
Nucleal	1.000N	1.00
Extranucleal	1.385N	0.90
Extranucleal	1.770N	0.80
Extranucleal	4.850N	0.00

# **Habitability Axis Plate**



# M002 - Stars — 06 Relating the Nucleal and Perannual Years

We have explored both <u>The Nucleal Orbit</u> and <u>The Perannual Orbit</u>. These two are not *limiting distances*, but **orbital environs** which both describe and contribute to the ontosomic nature of planemos.

As a quick review:

 Nucleal Orbit: that orbit (expressed in AU) at which a planemo receives from its star(s) the same radiant flux as Earth receives from the Sun at one Astronomical Unit distance, calculated by:

$$N = \sqrt{L}$$

Where L = Luminosity of the star(s) as expressed in Solar units,  $\odot$ 

• **Perannual Orbit**: that orbit (expressed in AU) which has an orbital period of exactly one sidereal Earth year, calculated by:

$$A=\sqrt[3]{M+m}$$

If we disregard the mass of the planemo *m*:

$$A=\sqrt[3]{M}$$

And we saw in M002 - Stars — 02 Parameters that through relationship:

$$M=\sqrt[3]{L}$$

This means that:

The perannual orbit can be approximated directly from the luminosity by:

$$Approx\sqrt[3]{\overline{\lambda}L}pprox\sqrt[6]{L}$$

• The nucleal orbit can be *approximated* directly from the mass by:

$$N pprox \sqrt{M^3}$$

And, by extension either can be approximated from the other by:

$$Approx \sqrt[6]{N^2}pprox \sqrt[3]{N} \ Npprox A^3$$

#### REMEMBER

- Both N and A are measured in astronomical units, not time!
- These last four equations are approximations; in most cases they'll be "accurate enough", but calculating N and A robustly is always advised.

## M003 - Binary Systems

Solar analog stars are more often found in binary or multiple systems than not, with over half exhibiting multiplicity.

- Duquennoy & Mayor (1991) originally found that approximately 57% of solar-type stars (spectral types F6–K3) in the solar neighborhood are part of binary or higher-order systems.
- Raghavan et al. (2010) updated this with modern data, reporting:
  - ~44% as binaries
  - ~11% as triples or higher
  - → Yielding a total multiplicity fraction of ~55% for solar-type stars.

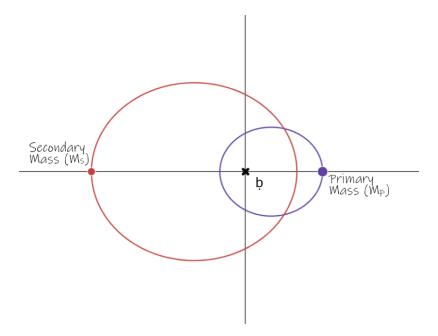
Statistically, stars comparable to the Sun are more likely than not to belong to binary or multiple systems—a pattern that profoundly influences system architecture, orbital stability zones, and the landscape of potential habitability.

This section focuses on binary systems, both stellar and planemo. While higher-multiplicity arrangements are common and fascinating, they introduce significant mathematical and physical complexity beyond the current scope of practical thesiastics. Even binaries alone present formidable obstacles to stable, life-supporting worlds—but to omit them would be to overlook one of the most consequential configurations in stellar system design.

## **The Basics**

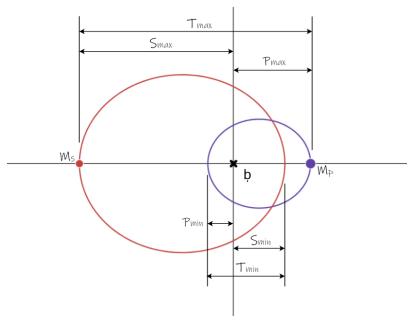
Binary systems consist of two bodies bound in mutual gravitational relationship, each tracing an orbital path around a shared center of mass known as the **barycenter** ( $\dot{p}$ ). This point, shown as a black X in the figure, *always* lies along the line connecting the centers of the two bodies and is not a massive object itself, but a calculated position determined by the masses and separation of the components.

The more massive object (the **primary body**) orbits closer to the barycenter, while the **secondary body** traces a larger path on the opposite side. Both orbits are elliptical, share the same eccentricity ( $\epsilon$ ), and are synchronized in period, preserving the balance of angular momentum.



A binary system is described by a total of nine dimensions (average dimensions not illustrated):

- $T_{min}$  ,  $T_{avg}$  ,  $T_{max}$  : The minimum, average, and maximum separations of the two bodies from one another
- $P_{min}$ ,  $P_{avg}$ ,  $P_{max}$ : The minimum, average, and maximum separations of the **primary** body (*P*) from the **barycenter** ( $\dot{p}$ )
- $S_{min}$ ,  $S_{avg}$ ,  $S_{max}$ : The minimum, average, and maximum separations of the **secondary** body (*P*) from the **barycenter** (b)



These are related through a series of equations which may seem daunting at first, but are quite straightforward once they are understood.

## **Primary Dimensions**

$$egin{aligned} P_{min} &= P_{avg}(1-e) = T_{avg}(1-e) \left(rac{M_s}{M_p+M_s}
ight) = T_{min} \left(rac{M_s}{M_p+M_s}
ight) = T_{max} \left(rac{M_s}{M_p+M_s}
ight) \left(rac{1-e}{1+e}
ight) \ P_{max} &= P_{avg}(1+e) = T_{avg}(1+e) \left(rac{M_s}{M_p+M_s}
ight) = T_{max} \left(rac{M_s}{M_p+M_s}
ight) = T_{min} \left(rac{M_s}{M_p+M_s}
ight) \left(rac{1+e}{1-e}
ight) \ P_{avg} &= rac{P_{min}}{1-e} = rac{P_{max}}{1+e} = T_{avg} \left(rac{M_s}{M_p+M_s}
ight) \end{aligned}$$

#### **Secondary Dimensions**

$$egin{aligned} S_{min} &= S_{avg}(1-e) = T_{avg}(1-e) \left(rac{M_p}{M_p+M_s}
ight) = T_{min} \left(rac{M_p}{M_p+M_s}
ight) = T_{max} \left(rac{M_p}{M_p+M_s}
ight) \left(rac{1-e}{1+e}
ight) \ S_{max} &= S_{avg}(1+e) = T_{avg}(1+e) \left(rac{M_p}{M_p+M_s}
ight) = T_{max} \left(rac{M_p}{M_p+M_s}
ight) = T_{min} \left(rac{M_p}{M_p+M_s}
ight) \left(rac{1+e}{1-e}
ight) \ S_{avg} &= rac{S_{min}}{1-e} = rac{S_{max}}{1+e} = T_{avg} \left(rac{M_p}{M_p+M_s}
ight) \end{aligned}$$

### **Total (Overall) Dimensions**

$$egin{align} T_{min} &= T_{avg}(1-e) = P_{min} + S_{min} \ &= T_{avg}\left(rac{1-e}{1+e}
ight) = P_{min}\left(rac{M_p}{M_s} + 1
ight) = S_{min}\left(rac{M_s}{M_r} + 1
ight) 
onumber \end{aligned}$$

$$egin{align} T_{max} &= T_{avg}(1+e) = P_{max} + S_{max} \ &= T_{avg}\left(rac{1+e}{1-e}
ight) = P_{max}\left(rac{M_p}{M_s} + 1
ight) = S_{max}\left(rac{M_s}{M_p} + 1
ight) \end{array}$$

$$T_{avg} = rac{T_{min}}{1-e} = rac{T_{max}}{1+e} = P_{avg} + S_{avg} \ = P_{avg} \left(rac{M_p}{M_s} + 1
ight) = S_{avg} \left(rac{M_s}{M_p} + 1
ight) \ = P_{min} \left(rac{M_p + M_s}{M_s(1-e)}
ight) = P_{max} \left(rac{M_p + M_s}{M_s(1+e)}
ight) \ = S_{min} \left(rac{M_p + M_s}{M_n(1-e)}
ight) = S_{max} \left(rac{M_p + M_s}{M_n(1+e)}
ight)$$

## **Eccentricity Relationships**

In the equations below a subscript dot  $_{ullet}$  means any two matching parameters; e.g. if  $Max_{ullet}-Min_{ullet}$  means any maximum value minus any minimum value of the same , such as  $P_{max}-P_{min}$  .

#### System Eccentricity

$$egin{aligned} e &= rac{Max_ullet - Min_ullet}{Max_ullet + Min_ullet} = 1 - \left[rac{Min_ullet}{Avg_ullet}
ight] = \left[rac{Max_ullet}{Avg_ullet}
ight] - 1 \ &= rac{P_{max}(M_p + M_s)}{M_sT_{avg}} - 1 = 1 - rac{P_{min}(M_p + M_s)}{M_sT_{avg}} \ &= rac{S_{max}(M_p + M_s)}{M_nT_{avg}} - 1 = 1 - rac{S_{min}(M_p + M_s)}{M_nT_{avg}} \end{aligned}$$

#### **Crossing Orbit Parameter**

The diamond  $_{\Diamond}$  subscript is used to indicate expressions in which all terms share the **same positional magnitude** (e.g., max, min, or average), regardless of parameter type.

$$cupe{e}=rac{M_p-M_s}{M_p+M_s}=rac{|S_\lozenge-P_\lozenge|}{S_\lozenge+P_\lozenge}=rac{|S_\lozenge-P_\lozenge|}{T_\lozenge}$$
 Where  $rac{M_s}{M_r}=0.8, cupe{e}\geq 0.8519$ 

 $\acute{e}$  (e-prime) is the system eccentricity value at which the orbits of the stars become *adjoined* tangential  $(e>0; M_p \neq M_s)$ 

#### **Limiting Eccentricity**

$$ar{e} = rac{T_{max} - 0.100}{T_{max} + 0.100}$$

$$T_{max} \geq 0.100 \left(rac{1+ar{e}}{1-ar{e}}
ight)$$

 $ar{e}$  (e-bar) is the largest system eccentricity that can be used with a given  $T_{max}$  , while ensuring that  $T_{min} \geq 0.100$ .

#### Forbidden Eccentricity

$$X_e \leq rac{B_0 - T_l}{B_0 + T_l} \quad | \quad X_e \leq rac{B_A - T_l}{B_A + T_l} \quad | \quad X_e \leq rac{B_N - T_l}{B_N + T_l}$$

Where:

$$ullet T_l = 4T_{max} = 4T_{avg}(1-e) = 4T_{min}\left(rac{1+e}{1-e}
ight)$$

 $X_e$  is the largest system eccentricity that can be used with a given  $T_{min}$ , ensuring that either the innermost habitable orbit ( $B_0$ ), the perannual orbit (A), or the nucleal orbit (N) lies beyond  $T_l$ .

#### **Quarles' Stability Limit**

$$Q_L = 0.08 T_{avg} = 0.08 \left(rac{T_{min}}{1-e}
ight) \quad | \quad e = 1-0.08 \left(rac{T_{min}}{L}
ight)$$

 $Q_L$  is the maximum distance a planet can orbit either star in a wide-binary system.

#### **Quarles' Eccentricity Limit**

$$Q_e=0.92$$

 $Q_e$  is the maximum eccentricity a wide-binary system can have while keeping  $T_{min} \geq Q_L$ .

## Sidebar — Albedo Estimates

Planet Type	Estimated Albedo (A)
Snowball planet	⟨0.6 ∧ 0.8⟩
Cloudy temperate Earthlike	⟨0.25 ∧ 0.35⟩

Planet Type	Estimated Albedo (A)
Rocky desert world	⟨0.15 ∧ 0.25⟩
Ocean planet (few clouds)	⟨0.050.15⟩
Thick sulfur clouds (Venus)	~0.75

# **Planetary Albedo Estimator**

Surface Type / Modifier	Base Albedo Estimate (A)	Notes
Fresh snow/ice	0.8	Highly reflective; contributes to snowball effect
Old snow / glacial crust	0.6	Still reflective but more absorptive than fresh snow
Desert (sand)	0.3	Can vary with mineral content and compaction
Grassland	0.2	Moderate reflectivity; varies with seasonal dryness
Forest (deciduous)	0.15	Dark under canopy; absorbs most light
Forest (coniferous)	0.13	Darker needles + canopy structure reduce reflectivity
Rocky surface	0.18	Can vary widely depending on coloration and texture
Ocean (high sun angle)	0.06	Absorbs most sunlight when directly overhead
Ocean (low sun angle)	0.2	Reflects more at shallow angles; up to 0.20 or more
Dense clouds (Venus- like)	0.75	Thick sulfuric clouds like on Venus; extremely bright
Thin clouds (Earth-like)	0.35	Cloud cover over oceans or land increases albedo
No clouds / clear sky	0.05	Near-minimal reflectivity, especially over ocean

# M009 - Sidebar — 04 Mind the Gap — The Shortcomings of the Traditional Spectral Scale

# Sidebar Module — Mind the Gap – The Shortcomings of the Traditional Spectral Scale

The classical stellar spectral sequence — O, B, A, F, G, K, M — originated as a cataloging system based on observed absorption lines in starlight. It was never designed to be linear, complete, or even particularly rational. And it shows.

- Spectral types weren't designed they accreted.
- Early classifiers like **Annie Jump Cannon** grouped stars by hydrogen line strength.
- Later work (e.g., by Morgan, Keenan, and Payne-Gaposchkin) retrofitted those types to surface temperature.
- The result? Inconsistent temperature spans, irregular gaps between classes, and no underlying mathematical symmetry.

## Consider the G–F Discontinuity:

- F9 → G0: Drop of only ~150 K
- F0 → F9: Nearly 1350 K
- · Linear? Not even close.

# **Why WBN Fixes This**

Worldbuilder's Notebook (WBN) adopts a linearized spectral system:

- Each spectral class is assigned a clean temperature range
- Subclasses divide that range evenly
- The system becomes interpolatable, predictable, and symbolically clear

#### This makes it easier to:

- Calculate stellar parameters from temperature
- Relate stars to their orbits and thermozones
- Avoid the awkwardness of stars that fall "between classes"
  - The WBN scale isn't astrophysically perfect but it's symbolically powerful, and consistently usable.

## **★** Bottom Line

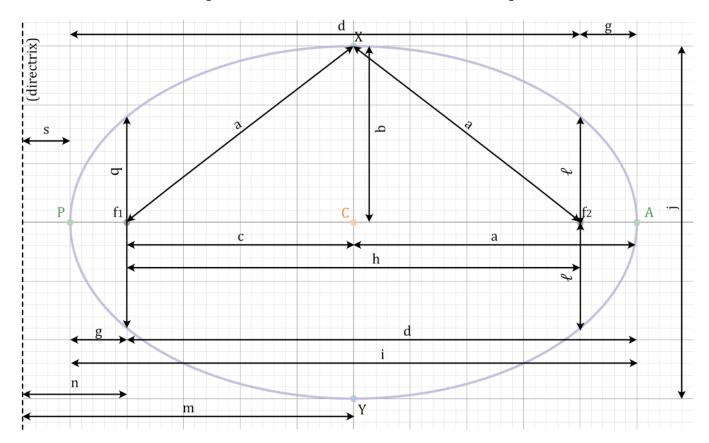
If your fiction or modeling needs the exact, messy mess of real-world classification? Use real-world data.

But if you need a system that supports symbolic structure, habitability logic, and easy computation?

Mind the gap.

Use the line.

# Sidebar — Ellipse Parameters and Equations



# **Ø Ellipse Geometry Solver — WBN Reference**

This reference provides a complete algebraic toolkit for solving any ellipse — geometric or orbital — from any two independent parameters. All terms match the diagram above.

# **Glossary of Ellipse Parameters**

All variables match the labeled diagram above.

#### Core Axes & Foci

- a semi-major axis
- b semi-minor axis
- c linear eccentricity (center to focus)
- **e** eccentricity (dimensionless) =  $\frac{c}{a}$ 
  - Describes how "stretched" the ellipse is.
  - e = 0  $\rightarrow$  perfect circle
  - $0 < e < 1 \rightarrow \mathsf{ellipse}$
  - $e = 1 \rightarrow$  parabola (degenerate case)
  - e > 1  $\rightarrow$  hyperbola (not an ellipse)
  - Eccentricity is unitless and invariant under scale.
  - It also defines the ellipse as a conic:

$$\frac{\text{distance to focus}}{\text{distance to directrix}} = e$$

- **f** flattening  $b = 1 \frac{b}{a}$
- i major axis = 2a
- ullet j minor axis =2b
- P, A primary vertices
- X, Y co-vertices (±b along minor axis)
- C center of ellipse
- $\mathbf{f}_1$ ,  $\mathbf{f}_2$  the two foci

## Derived Lengths

- **d** focus-maximus = vertex to opposite focus = a + c
- **g** focus-minimus = focus to nearest vertex = a c (e.g.  $f_1P$ )
- $\bullet \;\; \mathbf{h} \mathbf{m} \; \mathsf{focal} \; \mathsf{span} = 2c$
- $\ell$  semi-latus rectum  $=\frac{1}{2}q$
- **q** latus rectum  $= 2\ell$

## Directrix System

- **m** center-to-directrix  $= \frac{a}{e}$
- $\bullet \ \ \mathbf{n} \text{focus-to-directrix} = m c$
- **s** vertex-to-directrix =  $m a = \frac{c}{e} a$

# **Example 2** Canonical Equations

#### Geometric

• 
$$c = ae$$

• 
$$b = a\sqrt{1 - e^2}$$

• 
$$a=\sqrt{b^2+c^2}$$

## Orbital Geometry

• 
$$f = a(1 - e^2) = \frac{b^2}{a}$$

• 
$$r(\theta) = rac{a(1-e^2)}{1+e\cos\theta}$$

• 
$$r_p = a(1-e)$$

## Directrix Relationships

• 
$$m = \frac{a}{e}$$

• 
$$s = m - a = \frac{c}{e} - a$$

• 
$$n=m-c=\frac{\ddot{a}}{e}-c$$



## ■ What Is the Directrix?

For an ellipse, the **directrix** is:

A fixed vertical line such that, for any point PPP on the ellipse, the ratio of the distance from PPP to a focus and the distance from PPP to the directrix is equal to the eccentricity eee.

Formally:

$$\frac{\text{distance to focus}}{\text{distance to directrix}} = e$$

This defines the ellipse!



#### Where Is the Directrix?

There are **two directrices**, one on each side of the center, at a distance:

$$m = rac{a}{e}$$

... from the center, where:

a is the semi-major axis

• e is the eccentricity

So:

• Right-side directrix:  $x = \frac{a}{e}$ 

• Left-side directrix:  $x = -\frac{a}{e}$ 

If  $e \to 0$ , the directrix moves off to infinity — which makes sense, because a circle (eccentricity 0) has no directrix-like behavior.

## **Mathematical Methods of the Ellipse**

You can think of the ellipse as a set of points where:

$$\frac{PF}{PD} = e$$

Where:

- PF is the distance from a point P on the ellipse to a focus
- PD is the distance from that same point P to the directrix

This definition is symmetric and constructive: it's how conics are *defined* in classic geometry.



#### So What Does It Do?

The directrix is mostly a **definitional and constructional tool** — not something we see in physical orbits, but:

It gives us a clean formula for an ellipse in Cartesian coordinates:

$$r( heta) = rac{p}{1 + e\cos heta} \quad ext{where } p = rac{b^2}{a}$$

 It shows up in ray-tracing, parabolic reflectors, classical mechanics, and procedural shape generation.

## **Quick Facts**

Concept	Value / Equation
Directrix location	$x=\pmrac{a}{e}$
Distance center to directrix	$m = \frac{a}{e}$

Concept	Value / Equation
Distance vertex to directrix	$s = m - a = \frac{c}{e} - a$
Distance focus to directrix	$n = m - c = \frac{a}{e} - c$
Eccentricity via directrix	$e = \frac{PF}{PD}$



# **"Given Any Two, Solve the Rest" Matrix**

Each row lists two known parameters and what you can solve from them using canonical identities.

Known Pair	Solve For	Method / Equation(s)
a, e	b, c, f, m, s, n	$b=a\sqrt{1-e^2},\ c=ae,\ f=a(1-e^2),\ m=rac{a}{e},\ s=m-a,\ n=m-c$
a, b	c, e, f	$c=\sqrt{a^2-b^2}, \ e=\sqrt{1-rac{b^2}{a^2}}, \ f=rac{b^2}{a}$
a, c	b, e, m, s, n	$e=rac{c}{a},\ b=\sqrt{a^2-c^2},\ m=rac{a}{e},\ s=m-a,\ n=m-c$
b, c	a, e	$a=\sqrt{b^2+c^2},\ e=rac{c}{a}$
e, b	a, c	$a=rac{b}{\sqrt{1-e^2}},\ c=ae$
r <sub>p</sub> , r <sub>a</sub>	a, c, e, b	$a=rac{r_{p}+r_{a}}{2},\; c=rac{r_{a}-r_{p}}{2},\; e=rac{c}{a},\; b=a\sqrt{1-e^2}$
a, f	b, e	$b=\sqrt{af},\ e=\sqrt{1-\frac{b^2}{a^2}}$
a, m	e, c	$e=\frac{a}{m},\ c=ae$
c, e	a, b, m	$a=rac{c}{e},\ b=a\sqrt{1-e^2},\ m=rac{a}{e}$
a, s	m, e, c, b	$m=a+s,\ e=rac{a}{m},\ c=ae,\ b=a\sqrt{1-e^2}$
a, n	m, c, e, b	$m = n + c, \; c = m - n, \; e = rac{a}{m}, \; b = a \sqrt{1 - e^2}$

Note: This matrix is designed for symbolic manipulation. Some results require substitution into multiple chained equations.

# Sidebar — Anthropic Norm

The universe and its functioning as we currently perceive it, absent any extreme conditions.

#### The Anthropic Norm & the Mediocritic Principle of State

The vast majority of matter and energy in the universe exists within a narrow, statistically dominant band of physical states — from which it deviates only rarely and locally, within the current cosmological epoch.

This leads to two foundational insights for thesiastic modeling:

#### 1. Rarity is not normativity.

Extreme states — from black holes to degenerate matter — may be *numerous*, but they are not **norm-defining**. They are **local exceptions** to a global pattern.

#### 2. Normativity is modal, not mean.

The Anthropic Norm does not lie at the statistical *average*, but at the **modal cluster**: the zone in which **most matter and energy exist most of the time** under current universal conditions.

Thus:

- The universe is filled with stars, but is mostly not plasma.
   (It was at one time but that was a different epoch.)
- Neutron stars are real, but the universe is not mostly neutronium.
- Volatiles can form rocky planets but the cosmos is overwhelmingly hydrogen and helium in gaseous form.

## Sidebar — Equations for Worldbuilders

A reference sheet of exponent and logarithm rules useful in constructing systems of thermal, gravitational, orbital, and energetic relationships in scientifically-grounded worldbuilding.

# Rules of Exponents

#### + Product & Quotient Rules

$$x^m \cdot x^n = x^{m+n}, \qquad rac{x^m}{x^n} = x^{m-n}$$



$$\sqrt[n]{x}=x^{rac{1}{n}}, \qquad \sqrt[n]{x}=rac{1}{\sqrt[n]{x}}=x^{-rac{1}{n}}$$

$$\sqrt[m]{rac{x^n}{x^p}}=x^{rac{n-p}{m}}, \qquad \sqrt[m]{x^nx^p}=x^{rac{n+p}{m}}$$

## Power Rule

$$(x^m)^n = x^{mn}, \qquad (x^{-m})^n = x^{-mn}$$

$$\sqrt[n]{\sqrt[n]{x}} = \sqrt[nm]{x}, \qquad \sqrt[n]{x^{rac{1}{m}}} = x^{rac{1}{nm}}$$

## **Power of a Fraction**

$$\left(rac{x}{y}
ight)^n = rac{x^n}{y^n}$$

## **©** Fractional Exponents

$$\sqrt[n]{x^n}=x^{rac{n}{m}}, \qquad \sqrt[n]{x^m}=x^{rac{m}{n}}, \qquad (\sqrt[n]{x})^n=x^{rac{n}{m}}$$

## Negative Exponent Rule

$$x^{-n} = \frac{1}{x^n}$$

## Zero Exponent Rule

$$x^0 = 1 \quad ( ext{for } x 
eq 0)$$

## **∞ Infinity Exponent Rule**

$$x^{\infty}=\infty, \qquad x^{-\infty}=0$$

## Additional Useful Identities

# Distributive Rule for Exponents over Multiplication

$$(xy)^n=x^ny^n, \qquad \left(rac{x}{y}
ight)^n=rac{x^n}{y^n}$$

## Logarithmic Inverses

$$\log_b(b^x) = x, \qquad b^{\log_b(x)} = x$$

## A Logarithmic Expansion Rules

$$\log(xy) = \log x + \log y, \qquad \log\left(rac{x}{y}
ight) = \log x - \log y, \qquad \log(x^n) = n\log x$$

## **6** Reciprocal Roots

$$\sqrt[n]{rac{1}{x}}=rac{1}{\sqrt[n]{x}}=x^{-rac{1}{n}}$$

## Arbitrary Exponentials in Terms of e

$$a^x = e^{x \ln a}$$

# Powers and Logs

$$x^y = z \quad \Rightarrow \quad y = rac{\log z}{\log x} = \log_x z$$

$$x=z^{rac{1}{y}}=\sqrt[y]{z}$$

# **General-Use Equations**

## Variable Definitions

- **u** = upper bound
- I = lower bound
- **s** = sum of bounds (total)
- **d** = difference between bounds (span)
- **r** = ratio of lower to upper bound
- **m** = mean (average)
- **p** = product of bounds
- q = quotient of bounds

# Number Relationships 📏

#### + Ratio

$$ratio = \frac{l}{u} = \frac{\text{sum - difference}}{\text{sum + difference}}$$

#### + Sum & Difference Identities

$$ext{sum} = u + l = d\left(1 + rac{1}{r}
ight), \qquad ext{difference} = u - l = s\left(rac{1-r}{1+r}
ight)$$

#### Transformations Between Bounds

$$l=rac{s-d}{2}, \qquad u=rac{s+d}{2}, \qquad s=l+u, \qquad d=u-l$$

## Alternate Forms with Ratio

$$l=rac{s}{1+r}, \qquad u=rac{rs}{1+r} \ l=s\cdotigg(rac{1}{1+r}igg), \qquad u=s\cdotigg(rac{r}{1+r}igg)$$

0.01 - Introduct

$$l=rac{s-d}{2}, \qquad u=rac{s+d}{2}, \qquad l=rac{(s-d)\cdot r}{1+r}, \qquad u=rac{s\cdot r+d}{1+r}$$

Mean

$$m=rac{u+l}{2}, \qquad m=rac{s}{2}, \qquad m=u-rac{d}{2}, \qquad m=l+rac{d}{2}$$

**Inequality Notes** 

$$m\gg rac{1}{2}u \quad ( ext{if } u<0 ext{ and } l>0)$$
  $m=rac{1}{2}u \quad ( ext{if } l=0)$   $m=u=l \quad ( ext{if } u=l)$ 

× Product & Quotient

$$ext{Product} = xy = rac{s^2 - d^2}{4}$$
  $ext{Quotient} = rac{x+d}{x-d} = rac{(x+y) + (x-y)}{(x+y) - (x-y)}$   $rac{s}{d} = rac{x+y}{x-y}, \qquad rac{d}{s} = rac{x-y}{x+y}$ 

Percentage (p) from portion (x) of total (n)

$$p=rac{x}{n}, \qquad x=pn, \qquad n=rac{p}{x}$$

Definitions

- **p** = percentage
- x = portion (part)
- **n** = base number (whole)

# **©** Percentages in Ranges

Percentage (p) Represented by a Value (v) in Range (I ... u)

$$p=rac{v-l}{u-l}, \qquad v=p(u-l)+l, \qquad u=rac{v-l}{p}+l, \qquad l=rac{v-pu}{1-p}$$

#### **Variable Definitions**

- **v** = value within the range
- I = lower bound
- **u** = upper bound
- **p** = percentage of the ([l, u]) range represented by (v)

## Transfer a Percentage Between Two Ranges

## **General Equations**

Let:

- ( R\_1 = [\text{min}, \text{num}, \text{max}] )
- $(R_2 = [z, x, y])$ , where (x < z < y)

Then:

$$\mathrm{pct} = rac{\mathrm{num} - \mathrm{min}}{\mathrm{max} - \mathrm{min}}, \qquad z = \mathrm{pct} \cdot (y - x) + x$$

## Example

Given:

- (R\_1 = [0, 6, 10])
- $(R_2 = [4, z, 6])$

Then:

$$ext{pct} = rac{6-0}{10-0} = rac{6}{10} = 0.60$$
  $z = 0.60 \cdot (6-4) + 4 = 0.60(2) + 4 = 5.2$ 

Check:

$$\frac{5.2-4}{6-4} = \frac{1.2}{2} = 0.60$$

# Sums of Number Sequences

## **Variable Definitions**

- Σ = sum of all integers in the range (I ... u)
- **s** = sum of bounds: ( u + I )
- d = difference: ( u I )
- I = lower bound of range
- **u** = upper bound of range

## + Consecutive Integers from (I ... u)

$$s = u + l, \qquad d = u - l$$

#### **B** Summation Formulas

Basic:

$$\Sigma = rac{u(u+1)}{2} - rac{l(l-1)}{2}$$

Symmetric:

$$\Sigma=rac{l^2-1}{2}+rac{u^2+u}{2}, \qquad \Sigma=rac{(u+l)(u-l+1)}{2}$$

Sum in terms of (d) and (s):

$$\Sigma = rac{d+1}{2} s, \qquad \Sigma = rac{sd+s}{2}$$

Expanded forms:

$$\Sigma=rac{u^2+u}{2}-rac{l^2-l}{2} \ \Sigma=rac{(u^2+u)-(l^2-l)}{2}, \qquad \Sigma=rac{u^2-l^2+u+l}{2}, \qquad \Sigma=rac{u^2-l^2+s}{2}$$

# Integer Sequences and Special Transformations

## Consecutive Odd Integers (1 ... u)

$$\Sigma_o = \left(rac{u+1}{2}
ight)^2 = rac{u^2+2u+1}{4}$$

## Consecutive Even Integers (2 ... u)

$$\Sigma_e = \left(rac{u}{2}
ight)\left(rac{u}{2}+1
ight) = rac{u(u+2)}{4} = rac{u^2+2u}{4}$$

## **Example 2** Count of Consecutive Integers in Range (1 ... u)

$$\left\lfloor \frac{u-l}{2} \right
floor + 1$$
 for odd or even spacing

or for total count of integers:

$$\left| \left| rac{u-l}{2} 
ight| \cdot 2 + 1 = 2 \left| \left| rac{u-l}{2} 
ight| + 1$$

#### □ Percent Difference

$$\%\Delta = 100 \cdot rac{ ext{new} - ext{old}}{ ext{old}} = 100 \left(rac{ ext{new}}{ ext{old}} - 1
ight)$$

#### Involutive Transformation

Given:

$$y = \frac{1-x}{1+x}$$

Then:

$$x = \frac{1-y}{1+y}$$

This is its own inverse: (f(f(x)) = x)

## Percentage Inversion (Reciprocal Percentages)

If x% of y = y% of x, then:

$$\frac{x}{100} \cdot y = \frac{y}{100} \cdot x, \qquad x \cdot \frac{y}{100} = y \cdot \frac{x}{100}$$

# $lue{}$ Generalized Metallic Mean for Any Integer x

The traditional formula is:

$$N_x=rac{x+\sqrt{x^2+4}}{2}$$

This generalizes the golden ratio ((x = 1)), silver ratio ((x = 2)), bronze ratio ((x = 3)), etc.

Alternative equivalent form:

$$N_x=\sqrt{1+rac{x^2}{4}}+rac{x}{2}$$

This version is symmetric and may be more intuitive in nested radical systems.

## Point–Slope of a Line

Given two points:

$$P_1=\left(x_1,y_1
ight)$$

$$P_2=\left(x_2,y_2
ight)$$

## **Slope Formula**

$$m=\frac{y_1-y_2}{x_1-x_2}$$

## Point-Slope Form

$$y - y_1 = m(x - x_1)$$

Or rearranged:

$$y = m(x - x_1) + y_1$$

## 

$$y = mx + b$$

# Converting from Point-Slope to Slope-Intercept

Start with point-slope:  $y - y_1 = m(x - x_1)$ 

Distribute the slope:  $y = mx - mx_1 + y_1$ 

Group constants:  $y = mx + (y_1 - mx_1)$ 

Therefore:  $b = y_1 - mx_1$ 

Note: The subscripts vanish because their values get absorbed into the constant (b). The slope-intercept form still "remembers" your point — just more subtly.

# Example 1

Given:

- (P 1 = (4.85, 0))
- (P\_2 = (1, 1))

#### Step 1: Find the slope

$$m = \frac{0-1}{4.85 - 1} = \frac{-1}{3.85}$$

## Step 2: Use point-slope form

$$y-0=rac{-1}{3.85}(x-4.85)$$

## Step 3: Rearrange to slope-intercept form

$$y = \frac{-1}{3.85}x + \frac{4.85}{3.85} \approx -0.26x + 1.26$$

# Example 2

Given:

- $(P_1 = (0.5, 0))$
- (P 2 = (1, 1))

## Step 1: Find the slope

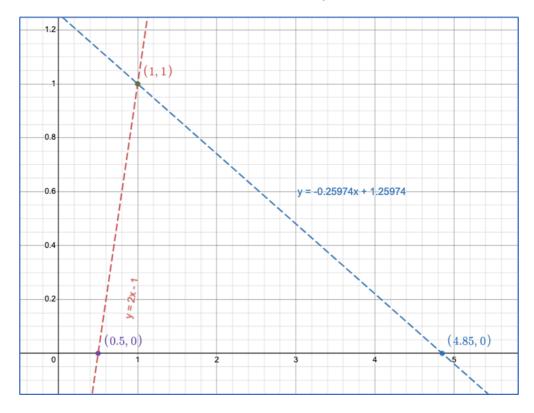
$$m = \frac{0-1}{0.5-1} = \frac{-1}{-0.5} = 2$$

## Step 2: Use point-slope form

$$y - 0 = 2(x - 0.5)$$

## Step 3: Rearrange to slope-intercept form

$$y = 2x - 1$$



This plot shows the two lines derived in the examples above:

Blue Line:

From 
$$P_1=(4.85,0)$$
 and  $P_2=(1,1)$   $y=-0.25974x+1.25974$ 

Red Line:

From 
$$P_1=(0.5,0)$$
 and  $P_2=(1,1)$   $y=2x-1$ 

They intersect at the point (1, 1), which lies on both lines.

## Temperature Scale Equalities

## Fahrenheit ↔ Kelvin

Core conversion equations:

$$C=K-273.15, \qquad C=rac{5}{9}(F-32)$$

So:

$$K-273.15=rac{5}{9}(F-32)$$

Or rearranged:

$$K = rac{5}{9}(F - 32) + 273.15$$

And:

$$F=rac{9}{5}(K-273.15)+32$$

## Worked Example (Convert 255.372 K to °F)

Start from:

$$K = 255.372$$

Plug into conversion formula:

$$K - 273.15 = \frac{5}{9}(F - 32)$$

$$-17.7778 = \frac{5}{9}(F-32)$$

Multiply both sides by 9:

$$-160 = 5(F - 32)$$

Divide by 5:

$$-32 = F - 32$$

So:

$$F=0^{\circ}\mathrm{F}$$

Alternatively, in reverse:

$$F=0 \Rightarrow K=rac{5}{9}(0-32)+273.15=-17.7778+273.15=255.372~{
m K}$$

#### **Nation** Fahrenheit ↔ Celsius

Standard conversion formulas:

$$F = rac{9}{5}C + 32, \qquad C = rac{5}{9}(F - 32)$$

#### Rearrangements:

From:

$$F = \frac{9}{5}C + 32$$

Subtract 32:

$$F - 32 = \frac{9}{5}C$$

Multiply both sides by 5:

$$5(F-32)=9C$$

Divide by 9:

$$C = \frac{5}{9}(F - 32)$$

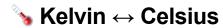
# Worked Example (Convert -40°F to °C)

0.01 - Introduction

$$C = \frac{5}{9}(-40 - 32) = \frac{5}{9}(-72) = -40$$

So:

$$-40^{\circ} F = -40^{\circ} C$$



The Kelvin and Celsius scales are offset by a constant:

$$K = C + 273.15,$$
  $C = K - 273.15$ 

**Note:** The size of 1 degree is identical in both scales; only the zero point differs. Water freezes at  $0 \,^{\circ}\text{C} = 273.15 \,\text{K}$  and boils at  $100 \,^{\circ}\text{C} = 373.15 \,\text{K}$ .

#### **Note:**

Temperatures on the Kelvin scale are written simply as  $\mathbf{K}$ , without a degree symbol. For example:

- Correct: 273.15 K √
- Incorrect: 273.15 °K or 273.15 degrees Kelvin

# Sidebar — Close-focus on Parameter Precedence Close-focus on Parameter Precedence

Elsewhere. I stated that

"Radius is an \_emergent property — the most flexible of the five core planemo parameters\*."

Here, we learn why that's the case.

WBN defines five core parameters for modeling planemos:

- Mass (m)
- Density (ρ)
- Surface Gravity (g)
- Escape Velocity (v<sub>e</sub>)
- Radius (r)

## **Physical vs Emergent Properties**

The first two — mass and density — are fundamental physical properties. If an object is composed of a specific material (e.g., pure iron), then:

- Its density reflects the compactness of that material under standard conditions.
- Its mass is the product of that density and volume.
   These values are not "fuzzy" they are determined by composition. But there's a complicating factor:

#### **Uncompressed Density in WBN**

In reality, high-mass planemos **compress themselves** under their own gravity. This self-compression:

- Increases core pressure
- Reduces actual volume
- Nudges the average (measured) density upward
   Unfortunately, the feedback between mass, gravity, and compression is:
- This feedback loop is nonlinear
- The corrections vary by material type
- And modeling it accurately requires complex equations of state
   WBN intentionally avoids this complexity in favor of practical worldcrafting.

#### **WBN Convention:**

We treat  $\rho$  (density) as the **uncompressed density** of the planemo — the intrinsic density of its materials assuming no internal gravitational compression.

This keeps  $\rho$  symbolically **independent** from m and allows us to calculate r, g, and  $v_e$  without recursive modeling. Compression effects are minimal within the Geotic range  $(0.5 \land 1.5) \oplus$ , so this simplification is physically tolerable and worldcrafter-friendly.

#### Parameter Precedence: A Symbolic Hierarchy

In WBN, we adopt a symbolic precedence system to clarify what depends on what.

#### First Precedence: Composition-Driven Parameters

- Mass (m)
- Uncompressed Density (ρ)
   These are primary constraints, based on:
- Material class
- Planetary category
- Biospheric plausibility

Narrative or symbolic intention

#### **Second Precedence: Experiential Parameters**

- Surface Gravity (g)
- Escape Velocity (v<sub>e</sub>)

These depend on m and  $\rho$ , and describe how a being would **experience** the world. They answer:

- "How heavy do things feel?"
- "How hard is it to launch something into space?"
   Because they're experiential, g and v<sub>e</sub> serve as thresholds for habitability and filters for narrative design.

For writers of SF, escape velocity might be of slightly greater import, as they are often more concerned with getting characters out of the planet's gravity well.

#### **Third Precedence: Emergent Parameter**

• Radius (r)

We treat radius as an **emergent quantity**, derived from the interplay between m and  $\rho$ . Once those are specified, r is computed using:

$$r=\sqrt[3]{rac{3m}{4\pi
ho}} \hspace{1cm} ext{Absolute Calculation} \ r=\sqrt[3]{rac{m}{
ho}} \hspace{1cm} ext{Relative calculation}$$

By defining  $\rho$  as uncompressed, we sidestep recursive compression modeling and free r to play its proper role as a derived result.

**In short:** Radius is not arbitrarily assigned in WBN — it emerges from first principles, and that's exactly what gives it flexibility.

However, if a planemo meets all other Geotic criteria but falls slightly outside the  $(0.5 \land 1.5) \oplus$  radius guideline, **there is room for flex** — especially when symbolic or experiential factors support it.

#### Surface Gravity, Escape Velocity, and Radius "Flexibility"

We maintain the general **Geotic envelope** of  $(0.5 \land 1.5) \oplus$  for all five core parameters. However — as discussed in **Example: When Good Values Go Bad** — not all combinations of any two parameters will yield outputs that remain Geotic.

To test this, we evaluated all combinations of **mass** (m) and **uncompressed density** ( $\rho$ ) within the Geotic range ( $(0.5 \land 1.5) \oplus$ ), using an increment of  $0.05 \oplus$  for each. From these, we calculated the corresponding:

- Surface Gravity (g)
- Escape Velocity (v<sub>e</sub>)
- Radius (r)

#### Results from Evaluated Combinations:

- Gravity (g) derived from m and ρ:
  - All values fell within the expected (0.5 ∧ 1.5)⊕ range.
- **Escape Velocity**  $(v_e)$  derived from m and  $\rho$ :
  - Calculated range was ⟨0.7071 ∧ 1.2247⟩⊕.
- Radius (r) derived from m and ρ:
  - Calculated range was ⟨0.6934 ∧ 1.4423⟩⊕.

#### Conclusion:

All outputs for g,  $v_e$ , and r computed from Geotic-range values of m and  $\rho$  remain within or closely near the  $\langle 0.5 \land 1.5 \rangle \oplus$  constraint window.

#### Reminder:

While mass and density serve as **primary constraints**, the values they generate for gravity, escape velocity, and radius are emergent — and may push right up to the edges of Geotic acceptability. Planemos with marginal values on one or more of these outputs may still qualify symbolically, depending on biospheric or narrative justification.

#### **Order of Parameter Calculation**

WBN allows you to begin with **any two** of the five core planemo parameters and calculate the remaining three. For example:

 You might specify a desired gravity (g) and radius (r) to match narrative or symbolic needs — and then calculate **mass**, **density**, and **escape velocity** from those. However:

#### Caution:

Mass (m) and uncompressed density  $(\rho)$  are treated as inflexible physical constraints in WBN. They must fall within the Geotic envelope  $(0.5 \land 1.5) \oplus$  to yield plausibly habitable worlds.

#### **WBN** Recommendation

#### Start with mass and uncompressed density.

These two parameters:>

- Reflect the physical composition of your planemo
- Are symbolically independent
- Guarantee valid outputs for g, v<sub>e</sub>, and r if kept within the Geotic range

By anchoring your model in m and  $\rho$ , you ensure that all derived parameters remain within acceptable bounds — streamlining your creative process and avoiding invalid combinations.

# Sidebar — An ε World

- If eccentricity is low (e < 0.10), no major seasonal variation through the year.</li>
- All days are the same length, everywhere, all year long.
- "Seasonal" constellations still occur, because the direction the "night side" of the planet faces still changes as it orbits.
- No change in the size of the star in the sky during orbit.
- From a stellar standpoint, the concept of a "year" would be meaningless
  - ONLY changes like the slow rotation of the night sky from night to night, or the period of a major moon would be available for calendrical development.

# Sidebar — Justifying Parahabitable Parameter Limits

We have specified that the five foundational parameters for terrestrial-class planemos are:

- Mass
- Density
- Surface Gravity
- Radius
- Escape Velocity

While <u>1.01 — Planet Classes</u> defines five envelopes — **Telluric**, **Geotic**, **Gaean**, **Rheatic**, and **Xenotic** — each with their own astrophysical and biological implications, this sidebar focuses on the rationale for preferring a narrower, *parahabitable* range:

$$\mathrm{parameter} \in \langle 0.5 \wedge 1.5 \rangle \oplus$$

This envelope is not meant to describe strict habitability in the Gaean sense. Rather, it defines a **flexible but centered range** where human life can be sustained or engineered, and where ecological and technological systems remain dynamically stable without extreme compensatory

mechanisms. It reflects not only biological tolerance, but also **civilizational viability** — balancing survivability, mobility, infrastructure, and long-term planetary homeostasis.

These ranges are further filtered through a **mirandothesiastic sieve** — one that refuses to sever scientific measure from lived perspective. The goal is not simply to model what could exist, but to prioritize what could *matter*: to ecosystems, to civilizations, to meaning-making beings.

The  $\langle 0.5-1.5 \rangle \oplus$  band is wide enough to encompass variation, but narrow enough to preserve structural coherence across simulations, worldbuilding systems, and narrative plausibility. It balances the gravitational, metabolic, atmospheric, and material constraints that shape whether a world feels *inhabitable* or merely *endurable*.

However, good scholarship requires more than assertion. It demands that we **justify** these limits — or at least **validate** them — using first principles, observed planetary behavior, and biospheric plausibility.

This sidebar examines the reasoning behind each boundary, explores edge cases, and outlines the physical, chemical, and ecological consequences of exceeding these thresholds.

#### **Mass**

#### **Below** ≈ 0.500⊕

- Inadequate Long-Term Atmosphere Retention
  - Lower mass means lower escape velocity, unless density is artificially high
  - Even with decent surface gravity, thermal escape and sputtering gradually strip the atmosphere
  - Solar wind may erode the upper atmosphere unless magnetic protection is present (which low-mass planets rarely have)
- Thin or Transient Atmospheres
  - CO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub>O vapor essential for warming and biochemistry are lost over geologic time
    - Even if the planet starts with an atmosphere, it won't necessarily **keep** it
    - Results in environments like:
      - Mars (0.107⊕ mass): thin CO₂ atmosphere, mostly lost
      - Mercury (0.055⊕): essentially no atmosphere
- Weak or Nonexistent Magnetosphere
  - Mass correlates with core volume and residual internal heat
    - Smaller worlds cool fast → solid cores → no dynamo

 No magnetic field → no deflection of solar wind → increased atmospheric loss and radiation exposure

#### Tectonic Shutdown

- Mantle convection requires internal heat and a sufficient pressure gradient
  - Low-mass worlds solidify quickly
  - Once tectonics stop:
    - Outgassing slows or ceases
    - CO₂ cycle halts → greenhouse regulation fails
    - Planet becomes geologically dead
  - Without active geology, habitable climates cannot self-stabilize

#### Orbital Vulnerability

- Low-mass planets are more susceptible to:
  - **Tidal locking** (especially around M-dwarfs)
  - **Orbital perturbations** (easily nudged by other bodies)
  - Catastrophic impacts (less gravitational buffering)

#### Atmospheric Chemistry Becomes Hostile

- Once light gases escape, heavier ones like sulfur or chlorine may dominate
  - No volcanism or weathering to regulate composition
  - You get toxic skies or inert ones but not breathable ones

#### Conclusion:

- Planemos below ~0.500⊕ mass face compounding risks:
  - Atmospheric loss
  - Magnetic weakness
    - Thermal stagnation
- They may be ontosomic for extremophiles but sustaining complex, Earth-like ecologies over billions of years is highly unlikely

#### **Above** ≈ 1.500⊕

#### Gravitational Consequences Amplify

- Increased mass usually means higher surface gravity, unless offset by low density
  - But for rocky worlds with ρ ∈ ⟨0.900 ∧ 1.500⟩⊕, higher mass = steep surface gravity rise
  - At 2.000⊕ mass with average density, gravity can reach (1.700 ∧ 1.900)⊕, breaching biomechanical and biochemical tolerances:

#### Escape Velocity Surges

Higher mass → higher escape velocity → retains volatiles too well

- H<sub>2</sub>, He, CH<sub>4</sub>, and other gases that Earth sheds easily are now gravitationally trapped
- Atmospheres become:
  - Massive, with crushing pressures
  - Chemically reducing, hostile to oxygen-based life
  - Opaque, dominated by haze or deep cloud decks

#### Atmosphere Transitions from Thin to Drown-y

- Surface pressure may exceed 100 bar, even with moderate outgassing
  - Water becomes supercritical no liquid water layer, just hot, dense steam
  - Radiative cooling plummets: even modest stellar flux creates runaway greenhouse conditions

#### Tectonic Systems May Overdrive

- Massive interiors = enormous thermal budgets
  - Some super-Earths may have:
    - Hyperactive tectonics → unstable continents, relentless volcanism
    - Or locked crusts from extreme pressure → stagnant lid planets
  - Neither scenario favors long-term habitability:
    - Volatile cycling is either too fast or too halted
    - Climate regulation fails

#### Surface Environments Become Energetically Hostile

- Extreme pressure gradients near the surface lead to:
  - Rapid erosion
  - Overcompression of minerals
  - Inhibition of prebiotic compartmentalization
    - Origin-of-life chemistry must happen under extreme conditions not conducive to Earthlike pathways

#### Solvent Stability and Chemistry Shift

- Water, ammonia, and other life-sustaining solvents may:
  - Only exist deep underground
  - Be chemically altered into less reactive or less structured forms
    - Biochemistry must adapt to unusual ionic balances, high viscosity, and low diffusion rates
      - Protein folding, replication, and compartmentalization all behave differently

#### Launch Barrier and Tech Suppression

- Escape velocity may exceed 25 km/s
  - Space access becomes technologically and economically prohibitive
  - Civilizations may be trapped planet-bound, or face extreme energy costs for satellite networks and off-world activity

Cultural evolution diverges as the cosmic horizon closes

#### Conclusion:

- Worlds above ~1.500⊕ mass may still be ontosomic but the surface environment becomes increasingly hostile to Earthlike biospheres.
  - Atmospheric pressures surge
    - Climate regulation breaks
  - Biochemistry must adapt or fail
  - Even if life emerges, the odds of it following a familiar trajectory are low. These
    are deep-gravity worlds, chemically rich but biologically unstable.

# Superhabitables and Mass: Beyond "Just Right"

In 2014, René Heller and John Armstrong proposed the existence of **superhabitable planets** — worlds that may be **more conducive to life** than Earth, even if not ideal for humans. These planets are theorized to exceed Earth's habitability not by matching its parameters exactly, but by surpassing them in specific, life-favoring ways.

### **Proof:** Definition:

A **superhabitable** world is one that provides **enhanced conditions** for the *emergence*, *proliferation*, *and persistence* of life — especially diverse, adaptive, and long-lasting biospheres.

In *Worldcrafting 101* terms, these may be considered **mega-ontosomic** worlds: not only capable of supporting life, but actively *better* at nurturing it.

### Key Mass-Linked Traits of Superhabitables

- According to Heller & Armstrong, ideal superhabitable worlds are:
  - Slightly more massive than Earth, typically (1.200 ∧ 2.000) ⊕, with upper candidates up to 3.000 ⊕
  - Geologically more persistent: higher mass leads to longer tectonic lifespans
  - **Thermally buffered**: more efficient retention of internal heat extends mantle convection and volcanism
  - Better magnetic shielding: large, slowly cooling cores sustain stronger and longerlived magnetospheres
  - Larger surface area: more room for ecological diversification, especially with flatter terrain
  - Thicker atmospheres: improved radiation shielding, more stable greenhouse effect

 More shallow seas: potentially broader tidal zones and nutrient-rich photic environments

#### Implications

- Mass increases above ~1.500 ⊕ usually signal rising risk, particularly for Earthlike surface biology. But for generalized ontosomic potential, the picture is more nuanced.
- A world with 1.600–2.000⊕ mass and moderate density (0.800 ∧ 1.100)⊕ may maintain:
  - Surface gravity in the ≈ (1.200 ∧ 1.400)⊕ range (still viable)
  - Escape velocity high enough to retain a thick but breathable atmosphere
  - Internal heat sufficient to power tectonics for billions of years

#### Tradeoffs

- Superhabitability does not mean superhuman-friendliness:
  - Biomechanical costs rise as gravity increases
  - Space access becomes difficult (high v<sub>e</sub>)
  - Photosynthetically active radiation may differ under cooler stars
  - **Dense, moist atmospheres** may favor different metabolisms and chemistries
- These are worlds where life flourishes, but not necessarily your life.
- \*\*Superhabitables are not exceptions to the Geotic envelope
  - They are edge-pushing optimals within a carefully constrained corner of it\*\*:

• Mass: ⟨1.200 ∧ 2.000⟩ ⊕

• **Density**: ⟨0.800 ∧ 1.100⟩ ⊕

• **Gravity**: ⟨1.100 ∧ 1.400⟩ ⊕

• Tectonics: Active over 5+ Gyr

Magnetosphere: Sustained by large convective iron core

• **Star**: Spectral class M0–G9 (mass ∈ ⟨0.359 ∧ 0.817⟩ ⊙)

#### Superhabitables challenge anthropocentric bias

- They show that habitability isn't a peak it's a plateau
- Mass above 1.500⊕ doesn't always push you into hazard space; under the right conditions, it creates biological opportunity. In such cases, higher mass may be not a warning sign — but an invitation.

# **Density**

**Below** ≈ 0.500⊕

#### Indicates a Volatile-Rich Composition

- Density < 0.500⊕ usually signals a world made of ice, silicates, organics, or gas —
  not rock and iron</li>
- Analog worlds:
  - Titan (ρ ≈ 0.330⊕): methane–ice hybrid
  - Callisto (ρ ≈ 0.330⊕): rock–ice mix
  - Ganymede (ρ ≈ 0.360⊕): stratified ice/rock interior
- These are low-gravity, poorly differentiated, and chemically reducing environments

#### Geostructural Weakness

- With low density, even a modest-mass world becomes bloated in radius
- This produces:
  - Low surface gravity
  - Shallow gravitational potential well
  - High susceptibility to atmospheric loss
- Solid surface may be thin, icy, or semi-liquid unsuitable for stable tectonics or topography

#### Escape Velocity Drops

- For a given mass, low density means large radius → lower vev eve
  - Gases like N<sub>2</sub>, O<sub>2</sub>, H<sub>2</sub>O vapor escape more easily
  - Atmosphere must be cold and massive to stay intact or supplemented by continual outgassing

#### High Insolation = Runaway Loss

- In warm stellar zones, low-density planets cannot retain atmospheres
  - Solar UV + X-rays strip volatiles rapidly
  - Left with:
    - Frozen surface (if far from star)
    - Dead core or gasless ice ball (if close)

#### No Long-Term Tectonics

- Low density → poor internal stratification
- May lack a distinct metallic core
- Internal heat generation is low; retention is worse
- No mantle convection = no plate tectonics = no carbon cycle = climate collapse
  - Crust may behave plastically or amorphously not enough rigidity to form continents or fault lines

#### Weak or Absent Magnetosphere

No iron core = no geodynamo

- Without magnetic shielding:
  - Solar wind strips atmosphere
  - Surface exposed to radiation
  - Volatiles sputtered into space

#### Surface Conditions Are Often Alien

- May lack solid ground entirely thick clouds over slush or ocean
  - Insolation often produces photochemistry, haze layers, and tholins
  - Light scattering, pressure gradients, and visibility differ dramatically from terrestrial norms
  - Weather and climate may be dominated by:
    - Sublimation/condensation cycles
    - Chemical storms
    - Cryovolcanism

#### Biochemical Challenges

- If surface temperature allows for solvents (e.g., methane, ethane, ammonia), these tend to:
  - Have low reactivity
    - Require extreme cold
    - Be incompatible with known Earthlike metabolism
- Biochemistry must adapt to:
  - Slow reaction rates
  - Limited energy gradients
  - Nonpolar solvent dynamics
- Possible but pushes us into radically exotic life territory

#### Psychophysical Environments Would Feel Surreal

- Movement feels effortless (low gravity) but fluids behave strangely
  - Visual perception altered by deep scattering and low-pressure optics
  - Weather systems sluggish or explosive depending on thermal regime
  - Noise transmission altered quiet, eerie landscapes, or rapid atmospheric thumps

#### Conclusion:

- Density below ~0.500⊕ means your world is likely an iceball, a gas-rich bloater, or a crust over a subsurface ocean.
- Even if mass or gravity fall within Geotic bounds, the planet's internal
- Such a world may be ontosomic, or even parahabitable, under exotic conditions but its suitability for Earthlike surface biospheres is nearly nil.

### **Above** ≈ 1.500⊕

- Strong Indicator of Iron-Heavy Composition
  - High density often means a large metallic core and a thin rocky mantle
    - Possible formation pathways:
      - Mantle stripping via giant impacts (Mercury is the classic example: ρ ≈ 1.684⊕)
      - Primordial metal-rich protoplanet that never accreted much silicate material
      - Volatile loss in early system formation
    - These planets are compact and massive for their size, with unusually high surface gravity
- Extreme Surface Gravity Even at Modest Mass
  - For a given mass, high density = small radius → gravity spikes
    - A 1.000 ⊕ mass planet with 1.8⊕ density has:
      - Radius ≈ 0.800 ⊕
      - Gravity ≈ 1.560 ⊕
      - Escape velocity ≈ 1.400–1.500 ⊕
  - These effects rapidly breach Geotic thresholds even with otherwise "Earthlike" mass
- Thin Crust. Shallow Mantle
  - A large core displaces rocky material → thin silicate crust
    - This limits:
      - Plate tectonics
      - Volcanism
      - Sequestration of volatiles and carbon
    - Without geological cycling, climate regulation becomes fragile or inert
- Weakened Tectonic Activity
  - Small mantle volume = low convective energy
  - Thin crust = stiff plates, more likely to lock into a stagnant lid regime
  - This halts long-term carbon cycling → no climate stabilization
- Retention of Atmosphere is a Mixed Bag
  - High gravity and escape velocity allow for:
    - Strong atmospheric retention
    - But risk of retaining undesirable volatiles (e.g., sulfur, chlorine, CO)
  - Without tectonics or outgassing, planet may lack:
    - Greenhouse gases
    - Surface pressure

Atmospheric replenishment

#### Intense Magnetic Field — If There's Enough Heat

- Big iron core = good dynamo if internal heat persists
- Magnetic fields may be strong, but short-lived unless radiogenic or tidal heating supplements them

#### Harsh Surface Environment

- High gravity compresses:
  - Atmosphere → thin vertical scale
  - Landscape → **low relief**, little vertical variation
  - Fluids → higher boiling points, increased viscosity
    - Surface weathering slowed, erosion minimized
    - Subduction may never initiate → no crustal recycling

#### High Gravity = Biomechanical Barrier

- Any life must be structurally robust from the start
- Movement, circulation, and metabolic flow all require more energy
- Evolutionary fitness shifts toward:
  - Compact morphologies
  - Dense cellular scaffolds
  - Slow-growing, high-efficiency systems
  - Larger multicellular organisms unlikely

#### Psychophysical Landscape

- Movement feels sluggish, heavy
- Drops fall faster, wind dies sooner, sound carries less
- Visual perception altered by atmospheric thickness and refractive index
- The world may look Earthlike but it will feel alien

#### Conclusion:

- Planets with  $\rho > 1.500 \oplus$  are metal-heavy, compact, and structurally intense.
- While they may retain atmospheres and shield themselves magnetically, their geology and surface conditions work against biospheric diversity and long-term climate stability.
- They may be ontosomic but their suitability for Earthlike life is tenuous, and their evolutionary trajectories are likely to be **slow**, **deep**, **and strange**.

# Density in Superhabitables

# $\bigcirc$ Ideal Density Range: $\rho$ ∈ $\langle$ 0.800 $\wedge$ 1.100 $\rangle$ ⊕

- This range suggests:
  - A composition slightly richer in silicates or volatiles than Earth

- A large enough metallic core to sustain a dynamo
- A thick enough mantle to power tectonics for billions of years
- A modest radius expansion that keeps surface gravity in the ⟨1.100 ∧ 1.400⟩ ⊕ range (still biomechanically plausible)
- This density window supports structural stability, energetic cycling, and ecological flexibility without pushing the planet into extremes.

### Why Not Lower ( $< 0.800 \oplus$ )?

- Suggests ice-rich or gas-dominated composition
  - May lack a dense core → no magnetosphere
  - Surface gravity likely drops too low for:
    - Atmospheric retention
    - Ecological complexity
    - Stable liquid water under moderate insolation
  - Better suited to parahabitable or anontogenic classification

### Why Not Higher (> $1.100 \oplus$ )?

- Indicates iron-heavy or mantle-stripped structure
- Often results from giant impacts → dynamically unstable past
- Crust and mantle may be too thin to support:
  - Long-lived tectonic activity
  - Robust outgassing cycles
  - Climate regulation via the carbon-silicate cycle
- Surface gravity may become biomechanically or chemically problematic

# Superhabitable Density Traits

Trait	Role in Superhabitability
Moderate density ⟨0.8 ∧ 1.1⟩⊕	Suggests healthy balance of core/mantle
Thick mantle	Supports long-lived tectonics and volcanism
Moderate core	Enables <b>stable magnetosphere</b> without rapid heat loss
Slightly low gravity (from radius– mass ratio)	Encourages diverse biospheres, easier movement
Retains volatiles without suffocating	Stable but breathable atmospheres, good greenhouse regulation

# **Gravity**

### **Below** ≈ 0.5⊕

- Poor Atmospheric Retention
  - A planet struggles to retain a dense atmosphere, especially light molecules like N<sub>2</sub> or O<sub>2</sub>.
- This leads to:
  - Thin or nonexistent atmospheres
  - Poor UV and radiation shielding
  - Thermal extremes (due to low heat retention)
- This is why Mars at 0.38⊕ gravity is parahabitable at best.
- Fluid Dynamics Break Down
  - Water doesn't flow the same way. Capillary action dominates over gravity.
  - Oceans and lakes become shallow and extremely wide, or may not form at all.
    - Rainfall becomes mist or vapor precipitation fails to "fall."
- Chemical Mixing and Atmospheric Stratification
  - Convection slows dramatically
  - Gas layers stratify, leading to atmospheric stagnation
  - Cloud formation and weather may cease entirely or become wildly unstable
  - Pollutants and volatiles don't disperse
- Magnetosphere Limitations
  - Lower gravity → likely smaller core mass → weaker or nonexistent magnetic field
- Combined with thin atmosphere → intense radiation exposure
- Even if life evolves here, it would need:
  - Buried habitats
  - Thick biofilms
  - Reflective skins or other defensive adaptations
- Conclusion:
  - A stable biosphere might evolve under (0.4 ∧ 0.5)⊕ gravity
  - But it's unlikely to support Earth-like ecologies with dynamic, large-scale multicellular life

### **Above** ≈ 1.5⊕

- Structural Collapse at Micro- and Macro-Scales
  - High gravity = relentless compressive stress

- Surface materials must resist:
  - Crushing forces
  - Steep gradients in pressure over short distances
  - Problem: Most prebiotic scaffolds (e.g., lipid membranes, fragile polymers) may never form or remain stable
  - Even successful structures might flatten, rupture, or shear from their own weight
- Life has to "start strong" but origin-of-life chemistry tends to be flimsy
- Atmospheric Flattening and Thermal Gradient Compression
  - Denser gravity = thinner vertical atmospheres
    - Scale height decreases
    - Vertical circulation gets squeezed
    - Result:
      - More violent surface convection
        - Rapid thermal gradients over short vertical scales
        - Surface becomes a storm-wracked, turbulent layer
  - High-pressure zones can compress volatile gases into chemical forms unusable by emerging life
    - The surface becomes chemically and thermally unstable
- Surface Temperature Amplification
  - Thinner vertical atmosphere → less vertical mixing
  - Higher surface gravity → greater atmospheric pressure at sea level
    - More efficient greenhouse trapping
  - Even modest insolation can produce runaway surface heating
  - Water (or other life-supporting solvents) may only exist at extreme pressures
  - The "Goldilocks" zone may exist only underground, if at all
- Energy Cost of Biomechanical Motion
  - Every movement costs more
    - Lifting limbs
    - Circulating fluids
    - Expanding membranes
  - Even molecular motion must fight stronger forces
    - Self-assembly becomes entropically disfavored
    - Viscosity and diffusion rates alter radically
  - Emergent systems must overcome gravity early, which is rare without complex enzymes or pre-existing structure
- Biochemical Constraints on Solvent Chemistry
  - Solvents like water, ammonia, methane compress differently

- Protein folding, membrane behavior, ion mobility all shift in high-pressure regimes
  - DNA/RNA analogs may not remain stable
- Origin-of-life reactions may favor different bonding dynamics
  - e.g., shift toward van der Waals dominance over hydrogen bonding
- Biochemistry gets weird, and maybe non-viable
- Tectonic Stagnation or Overactivity
  - High mass often implies greater internal heat
  - But strong gravity may:
    - Inhibit mantle convection (plate rigidity)
    - Or accelerate it (hyperactive resurfacing)
  - Either way:
    - Continents may never stabilize
    - Hydrothermal zones (origin-of-life hotspots) may never persist

#### Conclusion:

Biochemistry may become non-viable before complex organisms ever emerge.

### **Radius**

### **Below** ≈ 0.8⊕

- Implies a Compact or Iron-Rich Interior
  - A small radius with normal mass means high density
    - Suggests a large metallic core and thin rocky mantle
    - May result from mantle stripping, impact history, or metal-rich formation zone
- High Gravity at Modest Mass
  - Small radius concentrates surface gravity
    - Even a 1.000 ⊕ mass planet with 0.75⊕ radius yields:
      - Gravity ≈ 1.78⊕
      - Escape velocity ≈ 1.55⊕
  - Biomechanical, atmospheric, and tectonic thresholds breached early
- Visual and Sensory Compression
  - Shorter horizon: curvature more noticeable at sea level
  - Vertical topography feels exaggerated, even on modest peaks
  - Landscape may appear visually foreshortened

#### Lower Heat Retention

- Smaller surface area = faster heat loss
- Thin mantles cool quickly → tectonic lifespan may be short

- Mars is a good example: its small radius led to early core cooling and tectonic shutdown
- May require radiogenic or tidal heating to remain active

#### Tectonic Fragility

- Thin crust and small mantle volume limit:
  - Plate mobility
  - Outgassing
  - Volatile recycling
- Climate regulation is difficult to maintain

#### Strong Geodynamo — If Core Is Active

- High core-to-mantle ratio favors magnetic field generation
- But may cool rapidly without sufficient internal insulation

#### Psychophysical Signature

- World feels "dense," heavy, and intimate
- Horizons are close, curvature obvious
- Vertical relief feels steep and near, like standing on a ball
- Gravity and motion feel compressed and taxing

#### Conclusion:

- Worlds with R < 0.800⊕ are likely metal-rich, dense, and geologically challenged</li>
- They may offer magnetic protection, but are structurally compact
- · Climate cycling and biospheric stability are at risk, especially if tectonic life is short

### **Above** ≈ 1.2⊕

#### Suggests a Volatile-Rich or Low-Density Interior

- Large radius + modest mass = low density
  - Implies high ice or gas content
  - Possibly a rocky core with a bloated volatile envelope

#### Low Surface Gravity — Even at Earthlike Mass

- A 1.000 ⊕ mass planet with 1.3⊕ radius has:
  - Gravity ≈ 0.59⊕
  - Escape velocity ≈ 0.88⊕
- Volatile loss becomes more likely especially without magnetic field

#### Poor Atmospheric Retention

- Radius increase spreads gravity thinner
- Unless paired with very cold temperatures, gases are easily lost
- N<sub>2</sub>, O<sub>2</sub>, and even H<sub>2</sub>O vapor escape rapidly under stellar radiation

#### Internal Structuring May Be Weak

- · Large, icy planets may be poorly differentiated
- May lack a distinct core or layered mantle
- Tectonics and volcanism unlikely crust may be soft, slushy, or chaotic

#### Limited Magnetosphere

- Without a dense, rotating core, dynamo effects are weak or absent
- Solar wind strips volatiles; radiation reaches surface easily

#### Surface Conditions Are Vast, Flat, and Often Alien

- Wide horizons, low gravity, and weak terrain contrast
- Surfaces may consist of haze layers, cryomud, or semi-liquid plains
- Light diffusion, temperature layering, and visibility all feel "off"

#### Psychophysical Landscape

- Movement feels weightless, loose, or eerily effortless
- Falling is slow but resistance from terrain is minimal
- Visual perception dominated by long, flat horizons
- Weather may be either sluggish or chemically exotic

#### Conclusion:

- Worlds with R > 1.200⊕ are likely bloated, volatile-rich, or iceball-class
- They may support parahabitable subsurface oceans but Earthlike life is rare
- Biospheres would require extreme cold, deep shielding, or exotic chemistry to persist

# Radius in Superhabitables

## **Ø** Ideal Radius Range: R ∈ ⟨0.900 ∧ 1.100⟩⊕

- Balances surface gravity, tectonic stability, and biospheric potential
- A radius modestly larger than Earth (~1.05⊕):
  - Can soften surface gravity for a higher-mass world
  - Still retains volatiles effectively
  - Promotes more diverse terrain without introducing instability

#### Allows:

- Sufficient surface area for climate zoning
- Reasonable atmospheric scale height for breathing and weather
- Biomechanical feasibility for large, mobile lifeforms

### Why Not Lower ( $< 0.900 \oplus$ )?

- Compresses gravity
- Shortens tectonic lifespan
- Increases surface heat loss and curvature
- Makes weathering and sediment cycling more difficult

### Why Not Higher (> $1.100 \oplus$ )?

- Weakens gravity
- Reduces escape velocity
- Expands surface area but spreads mass thin
- Tectonics may fail from poor core–mantle structure

## Superhabitable Radius Traits

Trait	Implication
Slightly larger than Earth	Keeps gravity Earthlike for higher-mass worlds
Preserves volatile retention	While improving terrain diversity
Supports tectonics	If paired with healthy density and mass
Encourages climate zoning	Greater surface area allows biospheric niches
Smooth curvature but defined relief	Visually compelling, emotionally stable

# **Escape Velocity**

# What It Is — and Why It Matters

Escape velocity  $(v_e)$  is the speed a body must reach to completely escape a planet's gravitational influence without further propulsion. On Earth,  $v_e \approx 11.19$  km/s. This isn't just a rocket science number — it governs whether a world can:

- · Retain an atmosphere
- Allow for viable space access
- Support Earthlike solvent cycles

In WBN terms, escape velocity is a *constraint amplifier*. It binds together mass and radius, and exerts compound effects on chemistry, biospheres, and technology.

# Escape Velocity Scaling

The absolute escape velocity formula is:

$$v_e = \sqrt{rac{2GM}{R}}\$\$Where: -\$G\$isthegravitational constant -\$M\$istheplanet's mass -\$R\$istheplanet's mass -\$R$istheplanet's mass -\$R$$$

v\_e =\propto= \sqrt{\frac{m}{r}}

A dense, compact world has \*higher\* escape velocity. A large, low-density world may have \*surprisingly low\*

## Sidebar — Geotic Ground States

### **Geotic Ground States**

If you assume a value of 1 for any of the basic parameters, the equations for the other parameters simplify, as enumerated below.

Note: If any two core parameters equal 1 simultaneously, then all five must equal 1.

Mass: m = 1

$$ullet r=\sqrt{rac{1}{g}}=\sqrt[3]{rac{1}{
ho}}=rac{1}{v_{s}^{2}}$$

• 
$$\rho = \frac{1}{r^3} = \sqrt{g^3} = v_e^6$$

$$ullet g = rac{1}{r^2} = \sqrt[3]{
ho^2} = v_e^4$$

$$ullet v_e = \sqrt{rac{1}{r}} = \sqrt[4]{g} = \sqrt[6]{
ho}$$

# Density: $\rho = 1$

$$ullet \ r=g=v_e=\sqrt[3]{m}$$

$$\bullet \ \ m=r^3=g^3=v_e^3$$

$$ullet g=r=\sqrt[3]{m}=v_e$$

• 
$$v$$
e  $=g=r=\sqrt[3]{m}$ 

**Note**: When  $\rho = 1$ , the values of **radius** (r), **gravity** (g), and **escape velocity** ( $v_e$ ) are all numerically equal. The **mass** (m) is the cube of any of them.

Gravity: g = 1

$$ullet m=r^2=rac{1}{
ho^2}=v_e^4$$

$$r = \frac{1}{\rho} = \sqrt{m} = v_e^2$$

$$\rho = \frac{1}{r} = \sqrt{\frac{1}{m}} = \frac{1}{v_e^2}$$

$$v_e = \sqrt{r} = \frac{1}{\sqrt{\rho}} = \sqrt[4]{m}$$

# Escape Velocity: v<sub>e</sub> = 1

$$m = \frac{1}{\sqrt{\rho}} = \frac{1}{g} = r$$

$$r = \frac{v_e}{\sqrt{\rho}} = \frac{1}{g} = m$$

$$\rho = \frac{1}{r^2} = g^2 = \frac{1}{m^2}$$

$$g = \sqrt{\rho} = \frac{1}{r} = \frac{1}{m}$$

Radius: r = 1

$$egin{aligned} \bullet & m=g=
ho=v_e^2 \ egin{aligned} \bullet & v_e=\sqrt{g}=\sqrt{
ho}=\sqrt{m} \end{aligned}$$

**Note**: When  $\mathbf{r} = \mathbf{1}$ , the values of mass (m), gravity (g), and density  $(\rho)$  are all numerically equal. The escape velocity  $(v_e)$  is the square-root of any of them.

### **Paramount Geotic Worlds**

The most Geotic worlds — that is, the worlds most naturally suited for Earthling-human life — are those with g = 1.

Since Earth-normal gravity determines everything from blood pressure to biomechanical stress, a surface gravity of 1g minimizes physiological strain and habitat adaptation needs.

If you set **mass** as your primary parameter, the others resolve as follows:

$$egin{aligned} ullet & r = \sqrt{m} \ ullet & 
ho = \sqrt{rac{1}{m}} \ ullet & v_e = \sqrt[4]{m} \end{aligned}$$

Alternatively, if you begin by setting **density**, the remaining values are:

• 
$$m=\frac{1}{\rho^2}$$

$$egin{aligned} oldsymbol{v} & r = rac{1}{
ho} \ oldsymbol{v}_e & = rac{1}{\sqrt{
ho}} \end{aligned}$$

The equations above also allow determination of any of the three remaining parameters when two are initially set/chosen.

# Sidebar — Justifying The Geotic and Gaean Parameter Envelopes

# **Justifying The Geotic Limits**

In establishing the boundaries of the Geotic classification, we confront not merely a technical exercise in parameter selection but a philosophical act of declaration. These limits—defined in terms of mass, density, surface gravity, radius, and escape velocity—do not emerge arbitrarily from equations alone. They are sculpted from the convergence of empirical data, biological insight, and an interpretive philosophy of life's tolerances: an ontological bridge between observation and valuation.

Parameter	Symbol	Geotic Envelope (in Earth Units ⊕)
Mass	m	⟨0.30 ∧ 3.35⟩ ⊕
Density	ρ	⟨0.85 ∧ 1.25⟩ ⊕
Gravity	g	⟨0.60 ∧ 1.65⟩ ⊕
Radius	r	⟨0.60 ∧ 1.50⟩ ⊕
Escape Velocity	Ve	⟨0.65 ∧ 1.50⟩ ⊕

The Geotic envelope is broad enough to encompass worlds plausibly habitable to Earthlike life, yet not so wide as to dilute the concept of habitability into meaninglessness. The limits are drawn to include known extremes of terrestrial endurance — lower gravities where the human body remains functional, higher ones where it still stands upright; densities reflecting silicate-rich compositions without slipping into degenerate matter; radii that allow for diverse tectonics and geochemistry, yet remain below the gas giant threshold.

These ranges are further filtered through a mirandothesiastic sieve — one that refuses to separate scientific measure from lived perspective. We acknowledge the Anthropic Principle not as an excuse, but as a lens: life emerges within certain ranges because those ranges make life like us possible. The limits of what we call *Geotic* reflect both the statistical plausibility of

terrestrial-like biology and the philosophical humility to admit that even our constraints are narrative choices shaped by experience.

Indeed, the very act of defining limits implies both Logos and Mythos. In Logos, we justify bounds through physics and biology. In Mythos, we recognize that these bounds are meaningful precisely because we chose to give them meaning. Syncresis demands this integration—*est quod est*: the numbers are what they are, but the envelope is ours to declare.

To be Geotic is to stand within the habitable corridor of possibility — not at the narrow peak of Earth-perfect parameters (Gaean), nor flung to exotic extremes (Xenotic). It is the threshold of plausibility for Earthlike life in a cosmos that offers no guarantees but countless invitations.

# Sidebar — Objective Mass Scale

# **WBN Principle of Mass Measurement**

Planemo masses are purely numerically defined.

They **measure** a body's physical magnitude; they do **not categorize** or **qualify** its nature or type.

The following table defines the **official WBN symbolic mass intervals** — logarithmic divisions of planemo mass based on powers of ten relative to Earth  $(\oplus)$ . These are used for measurement and comparison only. They are **not categorical classes**, and do **not imply world type**.

Intervals	Min. Mass ≥	Max. Mass <	Power
deniterran	0.000000001	0.00000001	10 <sup>-10</sup>
nanoterran	0.00000001	0.0000001	10-9
oktiterran	0.0000001	0.000001	10-8
septiterran	0.0000001	0.000001	10 <sup>-7</sup>
microterran	0.000001	0.00001	10-6
pentiterran	0.00001	0.0001	10-5
demiterran	0.0001	0.001	10-4
milliterran	0.001	0.01	10 <sup>-3</sup>
centiterran	0.01	0.1	10-2
deciterran	0.1	1	10-1
terran	1	10	10°
dekaterran	10	100	10¹

Intervals	Min. Mass ≥	Max. Mass <	Power
hectoterran	100	1000	10²
kiloterran	1000	10000	10³
myriaterran	10000	100000	10 <sup>4</sup>
hexaterran	100000	1000000	10 <sup>5</sup>
megaterran	1000000	10000000	10 <sup>6</sup>
heptoterran	10000000	10000000	10 <sup>7</sup>
octoterran	10000000	100000000	10 <sup>8</sup>
gigaterran	100000000	1000000000	10°
denoterran	1000000000	10000000000	10 <sup>10</sup>
ondoterran	100000000000	1000000000000	1011
teraterran	1000000000000	10000000000000	10 <sup>12</sup>

#### Notes:

- 1. Where official SI prefixes exist (e.g. deci-, centi-, kilo-, mega-), WBN uses them directly.
- 2. For intermediate powers without SI prefixes, WBN adopts consistent **neologisms** based on the exponent's magnitude:.
  - Exponents **below zero** use an **-i** ending (unless overridden by SI, e.g. *micro*, not *micri*).
  - Exponents **above zero** use an **-o** ending (unless overridden by SI, e.g. *mega*, not *mego*).
- 3. While SI defines prefixes beyond **tera-** (e.g. *peta-*, *exa-*), WBN does not typically use them in planetary contexts. Even the observable universe spans only ~46.5 **giga**lightyears (Gly) in radius three orders of magnitude short of **teraterran** mass or volume relevance.
- 4. Conversely, the negative intervals are symbolically essential, as many moons, asteroids, and micro-planemos fall well below 1 ⊕ in mass. It is often more meaningful to say
  - "The body is 1 microterran (µ⊕)" than
  - "The body is **0.000001** ⊕".
- 5. For **practical purposes**, WBN defines the upper bound of each mass interval as **one demiterran (0.00001 ⊕)** below the next power of ten.
  - In other words, the *terran* interval spans from  $1.0 \oplus to 9.99999 \oplus$ .
  - Any value exceeding that threshold even slightly is considered to **round up** to the next symbolic interval.

#### Example:

 $9.9999901 \oplus \rightarrow 10.0 \oplus$ , placing the body in the **dekaterran** interval.

### The Microterran Scale

Because so many significant bodies in a planetary system have masses best expressed as a **millionth of a terran** ( $\mu\oplus$ ), WBN defines an optional *microterran scale* for intuitive symbolic modeling. This scale maps cleanly to the standard symbolic intervals and absolute powers of ten.

μ-terran Scale	Min. Mass ≥ μt	Max. Mass < µt	Standard Scale	Min. Mass ≥⊕	Max. Mass <⊕	Absolute Scale
demimicro	0.0001	0.001	deniterran	0.0000000001	0.000000001	10-10
millimicro	0.001	0.01	nanoterran	0.000000001	0.00000001	10 <sup>-9</sup>
centimicro	0.01	0.1	oktiterran	0.0000001	0.0000001	10-8
decimicro	0.1	1	septiterran	0.0000001	0.000001	10 <sup>-7</sup>
microterran	1	10	microterran	0.000001	0.00001	10-6
dekamicro	10	100	pentiterran	0.00001	0.0001	10-5
hectomicro	100	1000	demiterran	0.0001	0.001	10-4
kilomicro	1000	10000	milliterran	0.001	0.01	10 <sup>-3</sup>
myriamicro	10000	100000	centiterran	0.01	0.1	10 <sup>-2</sup>

### **Interpretive Guidance**

- The μ-terran scale improves readability and narrative clarity for small-mass bodies such as Vesta, Miranda, and Ceres.
- It is especially useful for planemos with masses between 10<sup>-6</sup> ⊕ and 10<sup>-1</sup> ⊕, where decimal
   ⊕ values become visually dense or cognitively opaque.
- This symbolic shorthand allows you to say:

"Ceres is about **157 microterrans** (157  $\mu$ t)" instead of "Ceres is 0.000157  $\oplus$ "

- However, even with this scaling, fractional expressions remain common at the lowest mass levels:
  - > "Miranda is approximately **0.001** µt in mass"

- > is still easier to read and parse than:
- > "Miranda is 1 demimicroterran in mass."

**In short:** The μt unit supports clarity without abandoning scalar precision — a vital aid to both symbolic modeling and thesiastic storytelling.

# **WBN** Canonical –mo Ontotypes

A classification of mass-based cosmic bodies by gravitational, structural, and fusion characteristics.

# Planemo

A gravitationally rounded object in the mass range typical of planets and planetary analogs.

#### • Mass Range:

 $0.000167 \oplus \leq m < 4.131 \text{ kt } (1.67 \text{ demiterrans to } 4.131 \text{ kiloterrans})$ 

- Fusion Status: No fusion
- Examples: Earth, Mercury, Ganymede, Kepler-22b
- Notes: May include isolated or satellite-bound bodies; includes dwarf planets and major moons above hydrostatic threshold.

# Intermo

A transitional-mass object between planets and stars.

#### Mass Range:

 $4.131 \text{ kt} < m \le 2.664 \text{ myt}$  (4.131 kiloterrans to 2.664 myriaterrans)

- Fusion Status: Sub-stellar; may fuse deuterium
- Examples: Brown dwarfs, isolated non-hydrogen fusors
- Notes: Symbolic "liminal" zone; fusion is partial or temporary.

# Stellamo

A self-luminous object that sustains hydrogen fusion at its core. The foundational unit of stellar systems.

#### Mass Range:

2.664 myt < m  $\le$  1 hxt (2.664 myriaterrans to 1 hexaterran)

- Fusion Status: Core hydrogen fusion
- Examples: Proxima Centauri, the Sun, Sirius A
- Notes: All main-sequence stars fall here; upper bound set by radiation pressure limits (~300 ⊙).

# Supermo

A high-mass monobody object that exceeds the stellar mass range but is **not yet galactic** in scope. Includes most known neutron stars and stellar black holes.

#### Mass Range:

 $1 \text{ hxt} < m \le 1 \text{ Mt} (100,000 \oplus -1,000,000 \oplus)$ 

- Common Forms:
  - Black Holes that have exceeded stellamo mass but not yet achieved ultramo mass

# Ultramo

A **supermassive** object — typically a black hole — existing at the centers of galaxies or as relics of early cosmic formation.

• Mass Range:

 $1 \text{ Mt} < m \le 1 \text{ Gt } (1 \text{ million} - 1 \text{ billion} \oplus)$ 

- Common Forms:
  - SMBHs

# Hypermo

A speculative class of **hypermassive monobodies**, potentially forming during early universe conditions or beyond current observational limits.

Mass Range:

 $m > 1 Gt (> 1 billion \oplus)$ 

- Speculative Examples:
  - Primordial hypercollapses
  - Direct-collapse black holes from Population III stars
  - Core seeds of hypermassive galaxies

# Summary Grid (Expanded)

Name	Prefix	Abbr.	Mass Range (⊕)
Stellamo	_	_	26,641 – 100,000
Supermo	super-	smt	100,000 - 1,000,000
Ultramo	ultra-	umt	1,000,000 - 1,000,000,000
Hypermo	hyper-	hmt	>1,000,000,000

# Classification Rule: The Monobody Condition

All WBN -mo ontotypes (planemo, intermo, stellamo, cryptomo) refer exclusively to individual, gravitationally coherent bodies — not to multi-body systems, collections, or regions.

### What Is a −mo:

A -mo is defined by:

- A single center of mass
- Internally unified gravitational structure
- Physically continuous volume (or event horizon, in the case of blackemos)
- E.g., planets, stars, brown dwarfs, neutron stars, black holes

### **♦ What Is Not a -mo:**

The following are **not –mo**, regardless of total mass:

Category	Example	Why Excluded
Star Clusters	Globular clusters, open clusters	Multi-body systems
Nebulae / Clouds	Giant Molecular Clouds (GMCs)	Diffuse, non-contiguous
Galaxies	Milky Way, Andromeda	Gravitationally bound aggregates
Binary Systems	Sirius A+B, Pluto-Charon	Contain ≥2 centers of mass
Black Hole Binaries	LIGO-detected pairs	Still system-level

# WBN Monobody Rule (Ontotype Scope Clarification)

All -mo classifications (planemo, intermo, stellamo, cryptomo) refer to individual, contiguous, gravitationally self-bound objects.

Multi-object systems — whether binary, ternary, or aggregate — are **not themselves -mos**, even if composed entirely of -mos.

# Key Principles:

#### 1. Ontotype is not emergent:

A **system of planemos** is not a larger planemo.

A **binary of stellamos** is not a megastellamo.

#### Modeling convenience ≠ ontological unity:

- For orbital mechanics, it's useful to model a binary pair as a single object of combined mass.
- But ontotypically, the barycentered abstraction is not a -mo.

#### 3. Distinct gravitational fields:

- A -mo has **one center of mass**, even if dynamic (e.g., fast-rotating planemo).
- A system has **multiple discrete gravitational centers**, even if mathematically reducible. For instance in a double-star planetary system, it is convenient to treat the two stellamos as a single stellamo of their combined mass, centered on the barycenter of their orbits, but there are not an *object* but a mathematical construct based on a property of the *system* they comprise.

#### Mirandion (M)

The smallest symbolically significant mass unit in WBN — equal to the mass of Uranus's moon Miranda.

It is both a numerothesiastic threshold  $(0.00001 \oplus)$  and a mirandothesiastic sigil of the smallest quantity that still transforms meaning.

The name resonates with *mirari* — "to marvel" — anchoring the Mirandion at the boundary of the measurable and the meaningful.

## Sidebar — Orbit Randomization

# **Orbit Randomization Notation**

This symbolic system defines how to procedurally generate a sequence of orbital radii using randomized multiplicative (or divisive) steps from a baseline (**basal**) value. It distinguishes between **intrabasal** (moving inward) and **extrabasal** (moving outward) orbit generation.

The notation is fully symbolic and compatible with WBN's randomization and range assignment grammar.

Intrabasal

$$r_i = B; \; \Omega = imes : \qquad r_{i-1} = rac{r_i}{\langle \langle \min \wedge \max 
angle 
angle} \quad ext{while } r_i \geq \Omega$$

**Extrabasal** 

$$r_i = B; \; \Omega = ext{ iny }: \qquad r_{i+1} = r_i \cdot \langle \langle \min \wedge \max 
angle 
angle \; \; \; ext{while } r_i \leq \Omega$$

Where:

- B = basal orbital radius (e.g. the nucleal orbit N)
- Ω = orbital distance cuttoff (minimum or maximum allowed orbit based on the star system constraints)

# Usage Strategy

The **intrabasal** and **extrabasal** forms can be used independently depending on your desired anchoring strategy:

Outward-Only Generation

If you begin at the **innermost permissible orbit** (e.g. a thermal, Roche, or design constraint), use the **extrabasal** form to expand outward via multiplicative steps:

$$r_0 =$$
 «innerlimit»;  $L =$  «systemedge»:  $r_{i+1} = r_i \cdot \langle \langle min \wedge max \rangle \rangle$ , while  $r_{i+1} \leq L$ 

Outward-Only Generation

If you begin at the **outermost permissible orbit** (e.g. a thermal or design constraint), use the **extrabasal** form to expand outward via multiplicative steps:

$$r_0 = ext{ innerlimit}; \; L = ext{ innerlimit} = ext{ innerlimit}; \; L = ext{ innerlimit} = ext{ innerlimit} = rac{r_i}{\langle \langle min \wedge max 
angle 
angle}, \; ext{while} \; r_{i+1} \leq L$$

Either method can fully define a system — or both can be combined with a central anchor (e.g. nucleal orbit) to scaffold a bidirectional structure.

# Sidebar — Physical Properties of Planemos Physical Properties of Planemos

There are five properties of planemos that can be thought of as *physical properties* — insofar as they describe the planemo physically or a property of the planemo that emerges from the other physical properties. These are:

1. Mass (m): The total amount of matter present. (Mass and weight are not the same —

weight depends on gravity; mass does not.)

- 2. **Density** (p): The average amount of matter per unit volume essentially, how tightly packed the planemo's materials are. This depends on both composition (e.g. rock, ice, metal) and, for larger bodies, gravitational self-compression.
- 3. *Radius* (r): The distance from the planemo's center to its surface. Technically, this is derived from the planemo's mass and average density but more on this in a moment.
- 4. **Surface Gravity** (g): The strength of gravitational acceleration at the planemo's surface how strongly it attracts objects located one radius away from its center.
- 5. **Escape Velocity** (v): The minimum speed needed to completely escape the planemo's gravity when starting from the surface how much velocity is required to leave the planemo entirely.

These are all intricately interrelated in ways that are much more complicated than we need to account for here. For instance, while **radius** *is* derived from **mass** and **density**, it also matters how strongly the mass of the planemo is gravitationally acting on itself. This causes *gravitational compression*, which means that the matter is forced into a denser configuration than it would otherwise exhibit *if it were not under such intense gravitational pull*. So, it is also true that **density** in some sense is derived from **mass** and **radius**.

Surface gravity and escape velocity are also very dependent on both mass and radius. The farther a point on the surface of the planemo is from the planemo's center, the less gravitational attraction from the planemo it experiences, decreasing according to the *inverse-square law* (more on this later). And the weaker the surface gravity, the less energy it takes to overcome it, so the lower the escape velocity.

For our purposes, it is reasonable to simplify things and say:

Radius is an emergent property of the interaction of mass and density.

... and not be too overly concerned about the subtleties.

Keppy: Sed ego dico, right?

Yes; this is our first official invocation of *sed ego dico*, "because I say". No, it's not *entirely physically accurate*, but it's good enough for what we need to accomplish.

Mass and density are also dependent upon what materials the planemo is made of: most planemos are composed of several materials (rock, ice, liquid water, etc.). Rock, itself, can composed of any number of more basic elements and compounds.

And all of these materials have their own inherent densities. Water, for instance, has a density of about 1.0 g/cm³ (and is, in fact the *standard* for material density in the metric system we're

using.) Iron, on the other hand, has a density of about 7.7 g/cm³ — almost eight times that of water. So 1 kilogram of water takes up more volume than one kilogram of iron.

There is an old riddle, which was a favorite of my maternal grandfather: "Which is heavier — a pound of iron or a pound of feathers?" The trick to the question, of course, is that both weigh a pound, but because feathers are less dense than iron, that pound (in its natural state) takes up far more volume than does the iron.

# Sidebar — Estimating Planetary Magnetospheres

- Magnetic moment (M) and how it relates to  $B_{surf}$
- Empirical scaling relationships (e.g., from Stevenson or Driscoll & Olson models)
- A simplified proportional form like:

$$B_{surf} \propto \left(rac{
ho_c}{
ho_\oplus}
ight)^p imes \left(rac{r_c}{r_\oplus}
ight)^q imes \left(rac{1}{d}
ight)^r$$

#### Where:

- $r_c$  = core radius
- $\rho_c$  = core density
- d = day length (rotation period)
- p, q, r are empirical exponents from dynamo scaling studies

This is a **scaling law approximation** from planetary dynamo theory — useful, but absolutely needing context.

#### Where This Comes From (Briefly)

This form is adapted from scaling relations used by geophysicists and planetary scientists (e.g., Olson & Christensen, Stevenson, Driscoll & Bercovici), who try to predict magnetic field strength based on **internal structure and heat flow**.

Values of p, q, and r vary depending on assumptions about:

- Core thermal convection mode (thermal vs. compositional)
- Rotational regime (rapid vs. slow)
- Efficiency of magnetic field generation

#### Rule-of-Thumb Exponent Ranges

Exponent	Typical Value (approx.)	Notes
p	⟨1.0 ∧ 1.3⟩	Reflects that higher-density cores produce stronger magnetic energy
q	⟨2.0 ∧ 2.5⟩	Core radius has a strong effect — bigger cores mean more dynamo volume
r	⟨1.0 ∧ 1.5⟩	Faster spin increases field strength, up to saturation

These aren't exact, but they give a ballpark for building **comparative models** — e.g.:

"A world with a core 1.2× Earth's radius, 1.1× Earth's core density, and a 16-hour day could have a magnetic field **2–3× stronger** than Earth's, all else equal."

#### Or simply provide example profiles:

- Earth:  $\rho$  = 1.0 $\oplus$ , d = 24h  $\rightarrow$   $B_{surf}$   $\in$  <25  $\land$  65>  $\mu$ T
- Super-Earth:  $\rho$  = 1.3 $\oplus$ , d = 16h  $\rightarrow$   $B_{surf}$   $\in$   $\langle$ 80 ..120 $\rangle$   $\mu$ T
- Mars:  $\rho = 0.71 \oplus$ , d = 24.6h  $\rightarrow B_{surf} \approx 0 \mu T$  (solid core)

# Sidebar — Range Constraints & Random **Assignment**

# Range Constraints & Random Assignment



### Core Constraint Classes

Туре	Symbol Form	Meaning	Example
Evaluative	x < y, x !≈ y	Truth test	Does x satisfy a condition?
Comparative	ΔT > 0	Descriptive comparison	Not used for enforcement
Prescriptive	x ≤. y	Should (soft rule)	Preferred but not required
Mandative	x .≤ y	Must (hard rule)	Required for validity

# Modifiers

! — logical negation (!=, !∈, !≈)

- . prefix mandative ( .≤, .∈)
- suffix prescriptive (≤., €.)

⚠ Do not combine ! with dot-prefixed/suffixed forms. Use the logical inverse instead (e.g., .>, >.).

# Range Connectives

Symbol	Meaning	Logical Form	Range Type
٨	Inclusive interior	a ≤	Closed range
<b>V</b>	Exclusive interior	a < 🗌 < b	Open range
<del>^</del>	Inclusive exterior	≤ a or ≥ b	Outside, includes bounds
<b>∀</b>	Exclusive exterior		Strictly outside
⊼	Left-exclusive interior	a < □ ≤ b	Half-open
Δ	Right-exclusive interior	a ≤	Half-open
⊽	Left-exclusive exterior	< a or ≥ b	Edge-grazing exterior
<u>v</u>	Right-exclusive exterior	≤ a or > b	Edge-grazing exterior

# **Random Assignment Syntax**

### **Basic Rule:**

Use  $\langle \langle \ \rangle \rangle$  to indicate **random value assignment** from a specified range.

Expression	Meaning
$x = \langle\langle a \wedge b \rangle\rangle$	Assign random value from a to b (inclusive)
$x := \langle \langle a + b \rangle \rangle$	Must assign value outside strict range
$x = \langle \langle a \land b \rangle \rangle$	Assign value in left-inclusive, right-excluded range

- = → assignment
- .= → mandated assignment (value must be generated)



### Precision Inference Rule

The decimal precision of a randomized result is inferred from the most precise range endpoint.

Syntax	Result Precision
$\langle\langle 1.4 \land 2.2 \rangle\rangle$	1 decimal place
⟨⟨1.40 ∧ 2.2⟩⟩	2 decimal places
⟨⟨1.400 ∧ 2.200⟩⟩	3 decimal places

This rule applies **even if the endpoints are excluded** from the valid output range.

# X Invalid Forms

Expression	Reason
$x = \langle\langle 1.414 \rangle\rangle$	X Invalid: one-value range
$x \in !\langle a \wedge b \rangle$	X Ambiguous: use → or → instead
x !.∈	X Invalid modifier stacking



### WBN Axiom 7.1 — The Symbolcrafter's Creed

"Better to have it and not need it than need it and not have it."

All range connectives, including obscure ones like v, are retained in W101 to ensure semantic closure and support future or edge-case modeling needs.



markdown

 $K_{\downarrow} \in \langle a + b \rangle$ 

Kirkwood Gap 1 must lie strictly between a and b (excluding both endpoints)

 $r := \langle \langle a + b \rangle \rangle$ 

Assign a randomized orbital radius outside a forbidden band

Sidebar — Orbit Randomization

# Sidebar — Land-Water Balance and Hydrospheric Patterns



Habitability is shaped by exposed land, not just crustal proportion.

A planet might have:

- The same total volume of felsic crust as Earth,
- The same hydrospheric volume,
- But very different levels of exposed land, depending on:
  - Sea level (absolute and relative)
  - Crustal relief
  - Tectonic activity
  - Isostatic balance
- Continents ≠ dry land "continent" in geologic terms just means buoyant crust, not exposed crust.
- Flooded cratons were common for the first half of Earth's history.
- True emergent landmasses may have been small islands or microcontinents for much of the Archean and Paleoproterozoic.
- Modern-style continents with wide uplands, deep interiors, and stable exposure are a Phanerozoic phenomenon.

### What "New Crust" Really Means

When we say:

"New crust is being created at mid-ocean ridges," we mean **oceanic crust** — specifically **mafic** basaltic crust — is forming as mantle material rises and cools.

But:

- This crust is dense and thin (≈ 7 km thick vs. ≈ ⟨30 ∧ 70⟩ km for continental crust).
- It sits lower in the gravitational field forming ocean basins, not continents.
- It does not increase exposed land area, unless...
  - It's uplifted by tectonic collisions (forming island arcs, terranes)
  - Or accreted onto existing continental margins

#### So:

- Q Oceanic crust = dynamic but low-lying
- Continental crust = buoyant and persistent

In fact, over time:

- Oceanic crust is recycled back into the mantle via subduction (lifespan: ~200 My)
- Continental crust tends to accumulate and endure, occasionally resurfacing in exposed terranes.

#### Is Felsic Crust Ever Subducted?

#### Yes... but reluctantly.

Felsic (continental) crust can be pulled into a subduction zone — but:

- It is less dense than oceanic crust (≈ 2.7 g/cm³ vs ≈ 3.0+ g/cm³)
- It is buoyant relative to the mantle
- It resists permanent subduction and tends to "jam" or "pop back up"

So when felsic crust **does** get subducted:

- It is often part of a complex terrane collision
- It may be scraped off and accreted to the overriding plate
- Or it may be partially melted, with lighter components rising back as felsic magma, contributing to continental volcanism

### Subduction-Driven Volcanism:

The **melt** from subducted slabs (mostly mafic oceanic crust + water-rich sediments) rises and:

- Interacts with the overlying continental lithosphere
- Mixes with or melts felsic components
- Produces andesitic to rhyolitic magma (more viscous and explosive than basalt)

This is why volcanic arcs (e.g., the Andes, Cascades, Japan) are:

- Continental in character
- Erupting felsic lavas, not oceanic basalt

# **W101 Summary Point:**

Continental crust is rarely destroyed.

When it's pulled into a subduction zone:

- It tends to resurface via volcanism,
- Or get welded onto other landmasses,
- Or form mountains via crustal thickening and uplift.

Over billions of years, this is how Earth built up its continents.

# 🥯 Why Some Rocks Are 3.7 Billion Years Old

Those ancient rocks in **Scotland**, **Greenland**, **Australia**, and **Canada** are part of what we call **cratons** — old, stable cores of continental lithosphere that have:

- Survived every tectonic rearrangement
- Resisted subduction due to buoyancy
- Avoided recycling into the mantle
- Often remained above sea level or \*\*only shallowly

These regions include formations like:

- The Isua Greenstone Belt in Greenland
- The Jack Hills zircon deposits in Australia
- The Lewisian complex in Scotland

They are made of **felsic or ultra-felsic rocks**, like granite and gneiss, and represent:

The surviving scaffolding of Earth's first continents.



- Oceanic crust is temporary it's made, spread, and subducted like conveyor belt parts.
- Continental crust is archival it builds up over time, preserves history, and keeps records.

So a 3.7-billion-year-old rock is a **literal relic** of the early Earth, untouched by recycling, uplifted by tectonics, and never drowned or subducted deep enough to erase its story.

- If your world has ancient exposed felsic terranes, it implies:
  - Very old crust (from early tectonic activity)
  - Long-term tectonic stability
  - Minimal subduction or high rates of crustal buoyancy
  - Possibly low sea level or uplifted interiors

# Sidebar — Units and Measures of Time

### Types of "Day"

An **ephemeris day** (**mean solar day**) is a unit of time used in astronomy and celestial mechanics defined as exactly 24 hours (86400 SI seconds).

Contrast this with an **apparent solar day (tropical day)**, is the time it takes for the Sun to appear in the same position in the sky, from one noontime to the next, and can be either as short as 23<sup>h</sup> 59<sup>m</sup> 38<sup>s</sup> (23.9938889<sup>h</sup>) or as long as 24<sup>h</sup> 30<sup>s</sup> (24.5<sup>h</sup>). Long or short days occur in succession, so the difference builds up until mean time is ahead of apparent time by about 14 minutes near February 6, and behind apparent time by about 16 minutes near November 3.

A **sidereal day** is a unit of time used in astronomy and celestial mechanics. It is defined as the length of time it takes for the Earth to make one complete rotation on its axis with respect to the *fixed stars*, and is defined as:

- · 86164.09053083288 SI seconds
- 23h 56m 4.09053083288s (23.93447192h)
- · 0.99726956632908d

A **stellar day** is Earth's rotation period relative to the International Celestial Reference Frame, defined by the International Earth Rotation and Reference Systems Service (IERS), as:

- · 86164.098903691 SI seconds
- · 23<sup>h</sup> 56<sup>m</sup> 4.098903691<sup>s</sup> (23.93446959<sup>h</sup>)
- · 0.99726966323716d

A sidereal day is 99.999902827% of a stellar day. The sidereal day is slightly shorter than the solar day due to the Earth's orbital motion around the Sun. The synodic period between them is slightly over 28000 calendar years.

The **synodic period** between the **ephemeris day** and the **sidereal day** calculates to almost exactly the tropical year.

... which calculates to only 0.265295200 seconds (1.00000000840688 times) longer than the actual value of 31556925.2507328s.

The **synodic period** between the **ephemeris day** and the **stellar day** calculates to very nearly the **sidereal year**.

... which calculates to only 101.65737 seconds (1.000003221 times) longer than the actual value of 31558149.7635456s.

# Sidebar — Why Venus Isn't Geotic



# Why Isn't Venus Geotic?

**Venus** is almost Earth's twin — in mass, radius, and gravity. Yet it is utterly inhospitable. Why?

Despite falling well within the **Geotic envelope** for:

Mass: m = 0.815 ⊕

• **Radius**:  $r = 0.949 \oplus$ 

• **Gravity**:  $g = 0.904 \oplus$ 

• **Escape velocity**: *v*<sub>e</sub> = 0.926 ⊕

• **Density**:  $\rho = 0.951 \oplus$ 

...Venus is not a Geotic world.

It is toxic, blisteringly hot, tectonically stagnant, and atmospherically crushing. Let's break down why **numbers alone aren't enough**.

# Hellish Surface Temperature

- T<sub>s</sub> ≈ 735K (462°C / 864°F) Hotter than Mercury, despite being farther from the Sun.
- This is due to a runaway greenhouse effect, not just solar proximity.
- CO<sub>2</sub>-rich atmosphere traps radiant heat extremely effectively.
- Clouds of sulfuric acid reflect sunlight but fail to cool the surface.

### Atmospheric Pressure ≈ 92 atm

- That's equivalent to being 900 meters underwater on Earth.
- The thick atmosphere imposes:

- Crushing surface pressure
- Fluid-like dynamics winds behave more like ocean currents
- Thermal insulation day–night temperature variation is negligible
- Water cannot exist in liquid form it either vaporizes or becomes supercritical.

# Chemical Hostility

- Atmosphere is >96% CO<sub>3</sub>
- Trace gases include SO<sub>2</sub>, HCl, HF, and virtually no water vapor
- The atmosphere is chemically reducing, not oxidizing
  - Photosynthesis as we know it is impossible
  - Most Earthlike biochemistry simply doesn't work

# Weak or Absent Magnetosphere

- Venus spins slowly: 1 Venus day ≈ 243 Earth days (retrograde!)
- This glacial rotation rate prevents strong dynamo action
- Result: No global magnetic field
  - Solar wind penetrates deep into upper atmosphere
  - Volatile loss, ion stripping, and atmospheric sputtering
  - May once have had water now likely gone

### Tectonic Inactivity

- No evidence of active plate tectonics
- Heat escapes via episodic resurfacing massive volcanic episodes that "reset" the crust
- No carbon-silicate cycle to regulate atmospheric CO<sub>x</sub>
- · No mountain formation, subduction, or seafloor spreading

## Psychophysical Impossibility

- The sky is yellowish-orange, clouded by acidic haze
- Visibility is minimal, often <1 km at surface</li>
- Sound propagation, fluid behavior, and light scattering are all radically non-Earthlike
- Walking on Venus is like walking in a high-pressure oven filled with corrosive fog



Because **numerical similarity** is not enough.

Geotic classification requires **functional habitability** — not just mass, radius, and gravity, but **biospheric potential**.

### Venus:

- Cannot retain liquid water
- Lacks plate tectonics
- Has a hostile chemical climate
- Offers no magnetic shielding
- Is far above tolerable surface temperatures

It meets all five **core parameters** — yet **fails nearly every dynamic requirement** for sustaining a complex, Earthlike biosphere.

# What This Tells Us

- Geotic parameters are necessary but not sufficient.
- We must consider:
  - Insolation
  - Atmosphere
  - Magnetosphere
  - Geological activity
  - Surface chemistry
  - Rotation and orbital dynamics
- These are explored in the <u>Sidebar Extended Geotic Habitability Guidelines</u>.

# Design Insight

Use Venus as your reminder that **numbers alone don't build worlds**. Habitability is **dynamic** — the interaction of physics, chemistry, and time.

# Sidebar — Retrograde Rotation and Axial Tilt (ε \_ 90°)

Keppy: Wait... isn't retrograde motion an orbital thing?

Not always. Planets can also **rotate** in a retrograde sense — spinning "backwards" compared to their orbital direction. And remember what is "up" in a star system is *purely a matter of convention*; ignoring direction of orbital motion, we could just as easily say that Venus is the only prograde planet in the Solar System.

# **Mow to Know:**

- Axial tilt (ε) is the angle between the planet's spin axis and the perpendicular to its orbital plane.
- If  $\varepsilon \in \langle 0^{\circ} \land 90^{\circ} \rangle$ , the rotation is **prograde** the planet spins the same direction as it orbits.
- If ε ∈ ⟨90° ∧ 180°⟩, the rotation is retrograde the planet spins the opposite direction from its orbit.

And here's the twist:

What we call "prograde" or "retrograde" is just a matter of **convention**.

We define "up" in the Solar System based on Earth's north pole and orbital direction. But that's completely arbitrary.

If we flipped the system and redefined "north" as "south," **Venus would become the** *only* **prograde planet**, and all the others would be retrograde.

# 🔌 Example: Venus

- Axial tilt: 177.4°
- Spins incredibly slowly and retrograde
- A full Venus day (sidereal) is ~243 Earth days
- But because of its retrograde spin, a solar day (sunrise to sunrise) lasts ~117 Earth days —
  and the Sun rises in the west!

# **6** Why This Matters

- ε > 90° radically changes day/night direction, sun path across the sky, and even cultural orientation ("sun rises in the west").
- High obliquity + retrograde spin = wildly different seasonal or diurnal patterns.
- For worldbuilders: this is a prime lever to make a world feel subtly alien while remaining physically plausible.

# **Marks** How It Works

- A planet's axial tilt (ε) is defined as the angle between its rotational axis and the perpendicular to its orbital plane.
- ε ∈ ⟨0° ∧ 90°⟩ → prograde rotation
   (spin direction aligns with orbital motion)
- ε ∈ ⟨90° ∧ 180°⟩ → retrograde rotation (spin direction opposes orbital motion)

### So:

- **Earth**:  $\varepsilon \approx 23.44^{\circ} \rightarrow \text{prograde}$
- Venus: ε ≈ 177.4° → retrograde
  - It's tipped almost completely upside down a rotation that is both slow and backwards
- Uranus: ε ≈ 97.8° → technically retrograde
  - Lies nearly on its side; its axial pole dips below the orbital plane

# 🖈 Retrograde Rotation at a Glance

Axial Tilt (ε)	Rotation Type	Example
0°	Perfectly prograde	Theoretical ideal
23.4°	Prograde	Earth
90°	Sideways / ambiguous	Theoretical (unstable)
97.8°	Retrograde	Uranus
177.4°	Retrograde	Venus
180°	Perfectly retrograde	Theoretical limit

# 🔍 Why It Matters

- ε > 90° affects day-night patterns, sunrise/sunset direction, and even seasonal progression.
- Can produce a "solar reversal" the Sun appears to rise in the west and set in the east.

 Combined with slow rotation, it may completely upend expectations about day length, thermal cycling, and climatic intuition.

# Sidebar — Extended Geotic Habitability Guidelines

There are other parameters that have to do with habitability:

Parameter	Value(s)
Average surface temperature (T <sub>s</sub> )	$T_s$ = 288K (standard unit) $T_s$ = 14.85°C $T_s$ = 58.73°F
Solar radiance (insolation) (Q) (annual average)	Q ≈1361 W/m² (top of atmosphere) Q ≈170-180 W/m² (surface)
Stellar luminosity (L)	3.828 × 10 <sup>26</sup> Watt 1.0 L⊙
Average atmospheric pressure (atm)	1 atmosphere (atm) 1 bar 101.3 kPa 14.6959 psi 1.0332 kg/m²
Atmospheric Scale Height (H) (more on this later.)	H = $8.5$ km $P(H) = 0.37^{H} \ P(km) = 0.37^{rac{km}{8.5}}$
Average atmospheric composition (idealized; varies with geologic era, biological evolution, and surface temperature)	Nitrogen (N <sub>2</sub> ) 78% Oxygen (O <sub>2</sub> ): 21% Argon (Ar)   Carbon dioxide (CO <sub>2</sub> ).   Water (H <sub>2</sub> O) vapor   $\approx$ 1% Ozone (O <sub>3</sub> )   Methane (CH <sub>4</sub> ), etc.
Atmospheric Ozone (O <sub>3</sub> )	Present in upper atmosphere
Axial Tilt/Obliquity (ε)	$\epsilon \approx 23.44^{\circ} \downarrow$ $\epsilon \in \langle 22.1 \land 24.5 \rangle / 41 \text{ ky}$ 10-12 ky to minimum
Rotational period/Length of day (d)	24 <sup>h</sup> (synodic) 23 <sup>h</sup> 56 <sup>m</sup> 4.091 <sup>s</sup> (sidereal)
Orbital Period (y) (all the variations explained later)	365 <sup>d</sup> 5 <sup>h</sup> 49 <sup>m</sup> 12 <sup>s</sup> (ephemeris) 365 <sup>d</sup> 5 <sup>h</sup> 48 <sup>m</sup> 45 <sup>s</sup> (tropical) 365 <sup>d</sup> 6 <sup>h</sup> 9 <sup>m</sup> 9.764 <sup>s</sup> (sidereal)

Parameter	Value(s)
Orbital Eccentricity (e)	0.0167 ↓ e ∈ $\langle 0.01 \land 0.0 \rangle / 413$ ky e ∈ $\langle 0.02 \land 0.05 \rangle / 100$ ky
Axial precession period (ψ)	25.772 ky
Magnetosphere (radiation shielding) ( $B_{surf}$ )	≈ ⟨25 ∧ 65⟩ µT (microtesla)
Land (lithosphere)-water (hydrosphere) proportion	30%-70%
Hydrospheric distribution	Five major oceans Numerous smaller seas

**Keppy**: Uh... wow. Not sure what to make of all that, frankly.

Yes, that's a lot.

**Keppy**: Can these be calculated for a fictional world?

Some; most not easily. Others are completely independent of the physical parameters (and each other, come to that). We can set some rules of thumb, as it were.

### **Extended Parameter Details**

### Average atmospheric composition

• (Please see Sideber Module – Planning A Detailed Atmosphere)

### Rotational period/Length of day (d)

- $d \in \langle 6^h \land 120^d \rangle$  General Geotic Range
  - $d \in \langle 6^h \wedge 48^h \rangle$  Human-adaptable; supports familiar circadian rhythms
    - d  $\in$   $\langle 2^d \land 20^d \rangle$  Mild extremes; thermal contrast can be buffered with atmosphere or oceans
    - d ∈ ⟨20<sup>d</sup> ∧ 100<sup>d</sup>⟩ Edge cases; require mitigation (dense atmosphere, global hydrosphere)
    - $d \in \langle 100^d \land 120^d \rangle$  Rare survivable zone
      - Habitability hinges on:
        - Efficient heat distribution (atmosphere or oceans)
        - Slow stellar heating (distant or cool star)
        - Non-volatile surface conditions
- Beyond 120<sup>d</sup>, the temperature contrast between day and night becomes too extreme for habitability without technological aid (which puts in the parahabitable spectrum).

- Even a perfect ocean-atmosphere system may fail to smooth the thermal tide.
- Planemos in this range may be Tellurics, but they are not Geotics.

**Keppy**: Do we know what other (if any) of a planemo's physical parameters may affect its rotational period?

As a matter of fact, astrophysicists are beginning to **simulate probable spin states** for Earth-like exoplanets under different formation conditions. A few recurring themes:

- Tidal locking is expected for planets in the habitable zones of M-dwarfs, due to proximity.
- Initial rotation rates may depend on:
  - Accretion history
  - Giant impacts (e.g., the Moon-forming event)
  - Early tidal evolution

### Resonant rotations

- Mercury's 3:2 spin-orbit resonance may be more common than full tidal locking
- Close-in planemos may be more likely spin slowly or be tidally locked
- Moons (especially those whose mass is a significant fraction of the planemo's) can stabilize or slow a planemo's rotation rate
  - This is happening with Earth; our day is lengthening by ≈ 17 microseconds per year, or 1 second every 58800 years
- Giant impacts can reset rotation direction and/or speed

### Orbital Eccentricity (e)

- $e \in \langle 0 \land 0.25 \rangle$  General Geotic Tolerance
- $e \in \langle 0.01 \land 0.10 \rangle$  Earth-clone ideal range
  - In multi-planemo systems, stable configurations usually result in e < 0.10 per planemo</li>
  - In single-planemo (only-child) or widely spaced systems, values up to e ≈ 0.25 may remain dynamically stable, but tend to reduce overall habitability
  - Risks of e > 0.25
    - Large insolation differentials between periastron and apastron
    - Pronounced climatic volatility
    - Less likelihood of maintaining persistent, stable biospheres
    - Increased vulnerability to orbital perturbations
    - Possible transit through and out of the system's habitable zone (HZ) during a single orbit
      - Note: On a world with zero axial tilt (ε = 0), high eccentricity might act as a surrogate for seasonal variation — producing orbit-phase-based temperature cycles. This is technically viable, but requires very careful

tuning of orbital shape, atmospheric thermal inertia, and surface conditions to avoid extreme or catastrophic conditions.

### Orbital Period (y)

This parameter can't be freely chosen — it's governed by Kepler's Third Law, originally formulated as

$$P^2 \propto a^3$$

and later regularized by Newton to account for the total mass of the system

• The orbital period depends on both the distance of the planemo's orbit and the *combined* masses of the star(s) and planemo.

$$P=\sqrt{rac{a^3}{M+m}}$$

where:

- P = the orbital period of the planemo in Earth years (y)
- a = the planemo's orbit's **semi-major axis** in **Astronomical Units**
- M = the mass of the star in solar units (⊙)
- m = the mass of the planemo (also in solar units)
- In most systems, m « M and can be neglected for quick calculations:

$$P=\sqrt{rac{a^3}{M}}$$

- ...However, if the planemo's mass exceeds ≈ 10% of the mass of the star(s), its contribution to the period of its orbit begins to have noticeable effects. This is especially relevant for:
- Super-Jovian mass planemos orbiting red-dwarf stars (q.v.)
- Binary planemo systems
- See Sidebar Module Two-body Systems
- See also Sidebar Module Double-planemo or Planemo-moon?
- I include *y* here not because it's adjustable, but because it's **crucial to the seasonal dynamics** of a world:
  - It modulates how axial tilt (ε) and eccentricity (e) express over time
  - It defines the length of seasons, and whether rotation (d) is fast or slow relative to the year
  - It affects the **precession timescale** (ψ) through long-term resonances
- In short: IF you declare y, that choice constrains what kind of star your system can have.
  - See Sidebar Module Stars, Planetary Orbits, and Habitable Zones for details
- Note that the masses of other planemos in the system have no effect in this equation!

### Obliquity (Axial tilt) (ε)

- $\varepsilon \in \langle 0^{\circ} \wedge 5^{\circ} \rangle$  Negligible seasonal variation
- $\varepsilon \in \langle 15^{\circ} \land 35^{\circ} \rangle$  Plausible range for active seasonal variation
- $\varepsilon \in \langle 20^{\circ} \land 30^{\circ} \rangle$  Earth-normal like
- $\varepsilon \in \langle 35^{\circ} \land 45^{\circ} \rangle$  Extreme seasonal variation unless mitigated by atmosphere/oceans
- ε > 45° Potentially unstable
  - Polar and tropical regions actually reverse!

A planemo does not *have* to have an axial tilt, but most do, because their mass isn't evenly distributed throughout their volume, and that mass is tugged on by the host star(s), companion Moons, other planets in their star system, etc.

### Obliquity Precession Period (ψ)

- $\psi \in \langle 15 \land 60 \rangle$  ky General Geotics range
- $\psi \in \langle 20 \land 30 \rangle$  ky Earth-clone ideal range
  - Note: If your planet has an axial tilt ( $\varepsilon \neq 0$ ), it will have an axial precession period.
- 5 ky
  - Too fast
  - Rapid climatic swings
  - Possibly preventive of long-term stable ecosystems
- 5 15 ky
  - Can support meaningful precession cycles
  - More frequent variation
- 20 30 ky
  - Earth-normal range
  - Ideal for familiar Milankovitch-style climate pacing
- 30 60 ky
  - Acceptible
  - Modulates long-term climate, but with slower variability
- 60 ky
  - May mute precessional influence
  - Planemo becomes dependent on  $\varepsilon$  or e (or a combination) for seasonal variation
- Habitability-Relevant Impacts of Axial Precession
  - Precession alone doesn't cause climate variation—but it modulates how obliquity and eccentricity combine with seasons.

- Precession rate is influenced by planetary tilt, mass distribution, rotation rate, and gravitational interactions (especially from moons or nearby planets).
- Moderately long precessional periods (25–30 kyr) help establish stable, regular
   Milankovitch cycles conducive to long-term ecosystem resilience.
- Affected by:
  - Axial tilt (ε) higher tilts tend to precess faster.
  - Rotation rate faster rotation yields a stronger equatorial bulge (which enhances precession).
  - Internal structure core-to-mantle mass distribution changes the planet's moment of inertia.
  - Gravitational interactions especially from moons or other planets in the system.

### Obliquity Azimuth (ບ)

- υ ∈ ⟨0° ∧ 359°⟩ Measure of the *directionality* of the planemos' obliquity relative to the periastron of its orbit.
- υ<sub>0</sub> is defined as the orientation when the plamemo's northern hemisphere is tilted precisely away from the star or system barycenter (b) (northern solstice) at periastron.
  - This is called periaptic zero.
- υ<sub>90</sub> would indicate that northern solstice has *precessed* 90° around the planemo's orbital path from **periaptic zero**.
- υ<sub>180</sub> would indicate that the northern solstice is occurring at *apastron*, the point in the planemo's orbit *farthest away* from the star/barycenter.
- IMPORTANT:
  - For  $\varepsilon_0$  planemos (they have no axial tilt),  $\upsilon$  is *undefined*, as there is no obliquity to precess.

### Precession Phase (τ)

- This is a measure of how far along in its precessional cycle a planemo is.
- Calculated by:

$$au = \left(rac{ extsf{o}}{360}
ight)\!\psi$$

### - IMPORTANT:

• For  $\varepsilon_0$  planemos (they have no axial tilt),  $\tau$  is *undefined*, as there is no obliquity to precess and no precessional duration to calculate a fraction of.

Relationship of ψ, υ, and τ:

$$egin{aligned} oldsymbol{arphi} &= 360 \left(rac{ au}{\psi}
ight) \ \psi &= rac{360 au}{arphi} \end{aligned}$$

### Magnetosphere (radiation shielding) ( $B_{surf}$ )

- $B_{surf}$  refers to the surface magnetic field strength, measured in microteslas ( $\mu T$ ).
  - For Earth, the typical surface field ranges between **25–65 μT**, depending on latitude and local crustal anomalies.
- $B_{surf} < 5 \mu T$  Unshielded; high cosmic radiation exposure, especially polar regions-
- $B_{surf} \in \langle 5 \wedge 20 \rangle \mu T$  Minimal shielding; planemo parahabitable without  ${\sf O_3}$  layer and/or thick tmosphere
- $B_{surf} \in \langle 20 \wedge 40 \rangle \mu T$  Weak field; still protective but slightly more porous
- $B_{surf} \in \langle 40 \wedge 70 \rangle \mu T$  Comparable to Earth; effective radiation shielding
  - $B_{surf} \in \langle 25 \wedge 65 
    angle \mu T$  Earth's typical magnetosphere strength range
- $B_{surf} \in \langle 70, \backslash ... 100 \rangle \mu T$  Significant shielding, but with growing secondary effects
- $B_{surf} > 100 \mu T$  Magnetosphere begins trapping too much radiation
  - Where the magnetosphere is concerned, there is such a thing as "too much of a good thing"; once the field strength exceeds ~100 μT, the magnetosphere may begin to trap radiation instead of deflecting it — causing the very problems it's meant to prevent.
- $B_{surf} > 400 \mu T$  Gas giant strength; radiation belts around planemo make space travel exceedingly hazardous.
- Why It Matters
  - A strong magnetic field deflects charged particles from the stellar wind, forming a magnetosphere.
    - Without this protection:
      - Atmospheric erosion increases (especially from solar UV and wind)
        - Surface radiation levels rise, particularly in equatorial and polar regions
        - Ozone layers and other protective atmospheric chemistry can degrade
      - Mars is the cautionary tale: once magnetically active, its core solidified early, its field collapsed, and it lost most of its atmosphere to space.
- What Generates It?
  - A planemo's magnetic field typically arises from a dynamo effect the movement of conductive fluid (usually liquid iron) in its outer core:
  - Requires:
    - Electrically conductive material
      - Rotation (faster helps)

- Active convection in the core (driven by heat and composition gradients)
- Influenced by:
  - Core size and composition (metallicity)
  - Rotation rate (d) faster rotation generally strengthens dynamo action
  - Internal heat flux related to mass, age, and radioactive element content
- See Sidebar Module Estimating Planetary Magnetospheres for details on estimating magnetospheres according to planemo parameters.

# **Continuation: Recommendations**

We mentioned above that "... radius is the most flexible of the parameters...," and that's true, since we're treating radius as an emergent property of the other parameters, specifically mass and density.

**Gravity**, on the other hand, is really the *least* forgiving of the parameters *for Geotic worlds*. But that deserves a moment's attention. We've specified that:

$$q \in \langle 0.5 \wedge 1.5 \rangle \oplus$$
,

but we didn't really explain *why* those are our bounds. What *are* the physical and biological implications of going beyond them? Let's look.

**Keppy**: But some life forms *might* still evolve on worlds like these...?

Yes, with the caveats listed above. The point, here, though, is that while gravities outside the g  $\in \langle 0.5 \land 1.5 \rangle \oplus$  range are *certainly* possible — even *probable* — and while life *might evolve* under these conditions, these worlds would be Tellurics in the *parahabitable* range, outside even *habitable*, and certainly not *hospitable to humans* which is our core criterion for **Geotic worlds**.

# Sidebar — Planning A Detailed Atmosphere Planning A Detailed Atmosphere Why Go Deeper Than The Basic Geotic Model?

You don't *have to* go beyond the basic Geotic model — unless, of course, your players or readers are the kind who pull out calculators and and gleefully point out why your planet's air shouldn't work.

If you're the kind of worldcrafter who likes knowing how things *actually work* (or just wants to stay one step ahead of the smart alecks), this Sidebar Module walks you through the

fundamentals of atmospheric plausibility.

We're sticking to **generally habitable atmospheres** here — ones that humans or near-humans could plausibly breathe. But the core principles apply no matter how exotic you want to get.

### Average atmospheric pressure (atm)

- Range: atm ∈ ⟨0.5 ∧ 2.0⟩
- Supports oxygen respiration and liquid water without requiring pressure suits or extreme acclimatization

### Atmospheric Scale Height (H)

- H ∈ ⟨6 ∧ 12⟩ km
- Governs pressure drop with altitude
- Affects breathing, mountain height, and high-altitude flight
- See below for details

### Average atmospheric composition

- Oxygen
  - Range: O₂ ∈ ⟨15% ∧ 30%⟩
    - 30% even damp fuel ignites more easily, and spontaneous combustion becomes a risk
    - < 15% requires acclimation or enhanced lung capacity (for any creature not evolved in the environment)
  - Needed for aerobic respiration
- Buffer Gas
  - Range: ∈ ⟨70% ∧ 85%⟩
  - The chemically inert or low-reactivity bulk gas that fills out the atmosphere around oxygen
  - Defines overall atmospheric density, scale height, sound propagation, and temperature response
  - Nitrogen (N<sub>2</sub>) and Argon (Ar) are your only reliable options
    - Other candidates (neon, helium, etc.) are too rare, too light, or too toxic

### Trace Gasses

- < 1%
- H<sub>2</sub>O vapor, O<sub>3</sub>, CH<sub>4</sub>
- CO<sub>2</sub> ideally should comprise < 0.04%</li>
- Required for climate regulation (greenhouse effect), UV shielding, biodynamics

# **More About Scale Height**

As related above, atmospheric scale height (H)

- Governs pressure drop with altitude
- Affects breathing, mountain height, and high-altitude flight

However, the value of H varies with the composition of the atmosphere because the *molecular mass* is different for each component gas and is not a constant.

**Hippy**: You need to calculate H based on how much O<sub>2</sub>, buffer gas, etc. your atmosphere has.

Exactly! So, how do you do that?

# **Calculating Scale Height**

Scale height (H) depends on:

- T = average temperature of the atmosphere (in Kelvin)
- M = mean molar mass of the gas mixture (in kg/mol)
- g = surface gravity (in m/s²)
- R = universal gas constant ≈ 8.314 J/mol·K

... related in the equation:

$$H = rac{RT}{Mg}$$

### **First**

Find the mean molecular (molar) mass M. Each gas in the atmosphere contributes to the average molar mass based on its **mole fraction**:

$$M=\sum x_i M_i$$

**Keppy**: DON'T PANIC! That  $\Sigma$  might look like calculus, but it's not... all it's saying is that we sum up the molar masses of all the gasses present

Yes, in the above equation:

- x<sub>i</sub> is the mole fraction of each atmospheric gas (in Earth's case, that's 0.78 for N<sub>2</sub>; 0.21 for O<sub>2</sub>)
- $M_i$  is the molar mass of the gas in question.

Let's use Earth's atmosphere as an example:

Atmosphere = 78% N<sub>2</sub>, 21% O<sub>2</sub>, 1% Ar (using kg/mol):

- $M_{N_2} = 0.028014$
- $M_{O_2} = 0.031998$
- $M_{Ar} = 0.039948$ 
  - We lump argon in with the trace gasses in Earth's case

$$M = (0.78 \times 0.028014) + (0.21 \times 0.031998) + (0.01 \times 0.039948) = 0.02896 \text{ kg/mol}$$

**Keppy**: Where did 0.028014, and the other numbers come from?

### Well spotted!

Each gas has a known molar mass — the mass of one *mole* of its molecules — and it's typically expressed in grams per mole (g/mol). Since we're working in SI units, we convert those to kilograms per mole (kg/mol) by dividing by 1000. And we look those numbers up in an appropriate (and reliable) source. Here are a few for reference:

Gas	Chemical Formula	Molar Mass (g/mol)	Molar Mass (kg/mol)
Nitrogen	N <sub>2</sub>	28.014	0.028014
Oxygen	O <sub>2</sub>	31.998	0.031998
Argon	Ar	39.948	0.039948
Carbon Dioxide	CO <sub>2</sub>	44.01	0.044010
Water vapor	H <sub>2</sub> O (gas)	18.015	0.018015
Methane	CH <sub>4</sub>	16.043	0.016043
Helium	Не	4.003	0.004003

**Hippy**: And you use these values in your atmosphere recipe to get your average molar mass.

Exactly! Once you've built your mix — say, 75%  $N_2$  and 25%  $O_2$  — just multiply each molar mass by its fraction and sum the results.

**Keppy**: Seems like that equation could get lengthy and complex.

You are *not* wrong about that. Getting warm and friendly with a spreadsheet or a programmable calculator is very good advice for the serious worldcrafter, for sure.

### Second

Now that we have our value for M, we plug it into our other *known* values for R (8.314), T (288), and g (9.8) and get:

$$H = rac{RT}{Mq} = rac{8.314 imes 288}{0.02896 imes 9.8} = rac{2395.6}{0.2838} = 8.44 ext{ km},$$

... which is usually rounded up to H = 8.5 km for convenience, but you can use the more exact value if you prefer.

**Hippy**: T = 288 K is for Earth. How does one determine it for a 'crafted planet?

Ah — excellent question.

The average surface temperature T depends on factors like:

- The luminosity and spectral class of the central star(s)
- The orbital distance of the planet
- The planet's albedo (reflectivity)
- And any greenhouse effects caused by atmospheric composition

That starts to pull us into stellar physics and orbital modeling, which is covered in:

### Module XY.Z — Building Your Star and Setting Your Orbit

There, you'll find methods for estimating a planet's **equilibrium temperature** and adjusting it for greenhouse gases to get a realistic T for your atmosphere model.

For now, if you're working with a roughly Earthlike setup, using:

$$T \in \langle 260 \wedge 320 \rangle K$$
,

or roughly  $\langle -13^{\circ} \wedge 47^{\circ} \rangle$ C will keep your numbers in a plausible range.

Here's some context for that range:

- 260K (-13°C; 8.6°F)
  - Close to the freezing point of seawater
  - Sustained habitability without deep-cold adaptation is still possible
- 273K (0°C; 32°F)
  - Freezing point of water
  - Important psychological and ecological threshold
- 288K (15°C; 59°F)
  - Earth's average
  - Serves as benchmark for climate comfort and live-rich biomes
- 310K (37°C; 98.6°F)
  - Human core temperature

- Upper limit for comfort under heavy exertion
- 320K (47°C; 116.6°F)
  - At or above this, heat stress becomes deadly without rapid evaporative cooling or climate control.
- ! Important note: IF you *choose* a surface temperature for your world, be sure to note it down, because it will help *determine* your star's parameters later!

**Keppy**: So, back to atmospheric composition: If you used argon instead of nitrogen as your buffer gas, the air would be heavier and H would shrink?

Exactly. More mass = more gravity per mole = thinner vertical spread = smaller H.

**Keppy**: And in this case, we're just ignoring the trace gasses altogether?

Mostly, yes — and here's why:

Trace gases like CO<sub>2</sub>, CH<sub>4</sub>, and H<sub>2</sub>O vapor are typically present in such **small quantities** (fractions of a percent) that they **barely shift the weighted average** of molar mass.

Let's say your atmosphere is:

- 78% N<sub>2</sub> (0.028014 kg/mol)
- 21% O<sub>2</sub> (0.031998 kg/mol)
- 1% CO<sub>2</sub> (0.04401 kg/mol)

$$M = (0.78 \times 0.028014) + (0.21 \times 0.031998) + (0.01 \times 0.04401) = 0.02899 \ \mathrm{kg/mol}$$

That's a difference of only **+0.00003** compared to Earth-normal — **Less than a tenth of a percent.** So, unless you're at CO<sub>2</sub> levels high enough to make the air toxic or unbreathable, it's safe to treat the trace gasses as negligible in the **H** calculation.

**Hippy**: So just include the big players — buffer gas and oxygen — and don't sweat the tenths of a percent?

Bingo. You can always do a full weighted sum if you really want to be *precise*, but for 99% of cases, O<sub>2</sub> and the buffer gas dominate the molar mass *for Geotic worlds*.

# Third: Pressure vs. Altitude Approximation

For Earth:

$$P(h)=P_0 imes 0.37^{rac{h}{H}}$$

Where:

- h = altitude in kilometers
- H = 8.5 (or 8.44) km

**Keppy**: What is P<sub>0</sub>, and how do we know its value?

Precisely the question I'd ask at this point!

 $P_0$  is the **surface pressure** of the planet — that is, the pressure at **zero altitude**. On Earth, that value is defined as:

- 1 atm
- 101325 Pa\*
- 101.325 kPa
- \* Named for Blaise Pascal; there's not space here to go into this in detail, but it's a fascinating read if you want to look it up!

For any world you create, P<sub>0</sub> is one of your **starting parameters**. You either:

- Choose it (e.g., 1.2 atm, or 0.65 atm), or
- Derive it from known gas composition, temperature, and gravity (which gets more advanced)

So, let's say you've chosen  $P_0$  = 0.9 atm for your planet, then at one scale height above the planet's surface, the atmospheric pressure calculates to:

$$P(H) = 0.9 \times 0.37 = 0.333$$
 atm

**Hippy**: Which raises the question of where 0.37 comes from?

Excellent question. That 0.37 isn't arbitrary — it's actually derived from a **fundamental mathematical constant**: Euler's number, e (≈ 2.71828).

The **pressure–altitude relationship** is an **exponential decay** equation. In its most general form:

$$P(h) = P_0 imes e^{rac{-h}{H}}$$

... which means that at an altitude of exactly one scale height (where h = H):

$$P(H) = P_0 \times e^{-1} = P_0 \times 0.3679$$

**Keppy**: Ah! I see... and  $P_0$  is just whatever multiple of Earth's surface pressure in atm you've chosen for your world!

**Hippy**: I always frown at "chosen"; is there any way to at least *approximate* an appropriate  $P_{n}$  for your planet based on how you decided to compose its atmosphere?

Well.... yes.... sort of.

You *can* approximate P0P\_0P0 from first principles — and it's especially useful if you've already defined your atmosphere's:

- Gas composition (molar mix)
- Surface gravity (g)
- Average temperature (T)

... and rearranging the *ideal gas law* for planetary atmospheres:

$$P_0=rac{
ho RT}{M}$$

But this requires knowing  $\rho$ , the **near-surface air density** — which in turn depends on pressure and composition, so we go a different route.

Instead, for an atmosphere in hydrostatic equilibrium, you can approximate:

$$P_0pprox rac{gMN}{A}$$

Where:

- g = surface gravity
- M = average molar mass (kg/mol)
- N = total moles of atmosphere
- A = surface area of the planet

But this, too, gets messy without knowing how much gas the planet *started with*, which is based on accretion, outgassing, escape velocity, etc.

So while you *can* try to derive it from theory — and I can help you do that — you're usually safe choosing a P0P\_0P0 based on:

- Your world's gravity (g)
- Its escape velocity (v<sub>e</sub>)
- Its molar mass and buffer gas makeup (M which we learned how to calculate above.)

Here's a "pressure plausibility chart" based on gravity and atmosphere type to give you an other "rule of thumb" to work from:

# Pressure Plausibility Chart

Rule-of-thumb surface pressures based on gravity and buffer gas makeup (M)

Gravity (g in g⊕)	Likely Pressure Range (atm)	Notes
0.5	⟨0.2 ∧ 0.6⟩	Light gravity; thinner atmosphere unless retained via cold temps or high mass gas
0.75	⟨0.4 ∧ 0.9⟩	On the thin side but potentially breathable; requires attention to $O_2$ %
1.0	⟨0.8 ∧ 1.2⟩	Earth-normal, depending on mix of gases and water vapor
1.25	⟨1.0 ∧ 1.5⟩	Denser air; easier to retain light gases like H <sub>2</sub> O, CH <sub>4</sub>
1.5	⟨1.2 ∧ 2.0⟩	Heavy air; pressure at sea level could approach adaptation limits

This assumes (!) an Earth-like atmosphere:

- Mean molar mass ≈ ⟨0.028 ∧ 0.032⟩ kg/mol
- Normal temperature (~288 K)
- Terrestrial radius (~1⊕)

You'll need to shift values worlds with high CO<sub>2</sub>, significant greenhouse buildup, or non-volatile-rich origins, but the above should be well within bounds for *Geotic worlds*.

# 1.00 — Setting The Stage

← 0.01 - Introduction

# A Little Background

# What Is A Planet?

Well, that depends on who you ask. Offically, according to the International Astronomical Union (IAU), as of 2006<sup>[1]</sup>, a planet is:

1. A planet is a celestial body that (a) is in orbit around the sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium

(nearly round) shape, and (c) has cleared the neighborhood around its orbit.

- 2. A dwarf planet is a celestial body that (a) is in orbit around the sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, (c) has not cleared the neighborhood around its orbit, and (d) is not a satellite.
- 3. All other objects, except satellites, orbiting the sun shall be referred to collectively as small solar-system bodies.

This (in)famously demoted Pluto from full planet status.

Items **1c** and **2c** are the crux of the debate, specifically the criterion for having "cleared the neighborhood around its orbit". Some people find that specification too limiting, or even artfully chosen specifically to single Pluto out, since it resides in the inner regions of the Kuiper belt and has several near neighbors, whereas the full planets of the Solar system do not (not counting moons).

Tim DeBenedictis in an article<sup>[2]</sup> at Space.com, makes a simple and compelling argument that the dividing line should be set more simply at objects of greater than 1000 km radius which independently orbit the Sun. At 1000 km radius, he says, the materials of which a body is formed (be they rock, ice, or metal) will start to deform under their own gravity and the body will become spherical(ish).

His definition is rather simpler than that of the IAU:

- 1. A planet is a celestial body that (a) is in orbit around the sun, and (b) has a maximum surface radius greater than 1,000 km (620 miles).
- 2. All other objects, except satellites, orbiting the sun shall be referred to collectively as small solar-system bodies.

I follow DeBenedictis' suggestion (though to avoid some of the complications of existing definitions, I adopt simplified terms):

- 1. A *planemo*<sup>[3]</sup> is a celestial body that (a) is in orbit around a star or stars, and (b) has a maximum surface radius greater than 1,000 km (620 miles).
- 2. All other objects, except satellites, orbiting a star shall be referred to collectively as *micromos* (small star-system bodies; SSSB moons, asteroids, comets, etc.).

...and I add the following proviso:

3. A **world** is a planemo that possesses a surface and/or atmospheric environment that is either **habitable** or **parahabitable**.

### **Habitable and Parahabitable**

I define a *habitable* a planemo as one which is **immediately habitable** by humans; people from Earth could land there, walk out of their craft in their shirtsleeves, and start hiking around learning about the place, its wonders ... and its dangers.

In contrast a *parahabitable* planemo is one that is **provisionally habitable** by human beings through the use of technology like atmospheric domes, pressurized subterranean habitats, etc., which are:

- 1. On or below the land or water surface; or,
- Suspended in the atmosphere by natural buoyancy or gravity-countering technology. In other words, the habitat must be in physical contact with the planemo — orbiting platforms do not render a planemo parahabitable.

In cases where either term applies, I'll often use the nomenclature (para)habitable.

**Hippy**: So, a world is a planemo, but a planemo isn't necessarily a world?

Oh, Hi, Hippy! I didn't know you were here! Friends, this is Hiparistarchus Ptolemeus Galileopernicum (Hippy to his friends — though he pretends not to like the nickname).

Yes, Hippy; that is a very good distinction. All *worlds* are *planemos*, but not all *planemos* are *worlds*. That is a good way to remember it, thanks!

BUT... micromos *can* be parahabitable. Make sense?

**Keppy**: Through the use of artificial living environments, right? But that would depend on the rest of the planemo's conditions, wouldn't it? I mean, if it's a lava planemo, it would probably need airborne habitats, rather than surface ones?

Aaaand, here's Keppy (Keplarius Braheus), right on cue.

Yes, Keppy; it can get to be a fuzzy definition — but that's really the fun of it. You're not locked in to a narrow set of choices... you can "fudge" as your needs require.

### **Terminology Focus**

In much of the published astrophysical literature, the word "size" is often used ambiguously. You'll often encounter a phrase like "an Earth-sized planemo". *Most of the time* "size" means radius, but on rare occasions, it is used to mean a planemo with the same *mass* as Earth, which is a very different quality. It's even worse when the word "big" is invoked... Does "this planemo is three times as big as Earth" mean "three times Earth's **radius**", or "three times Earth's **mass**"?

For our purposes, it is simpler to refer to the properties of a planemo in terms of multiples of the same property for Earth. So while Earth's mass is  $\approx 5.972 \times 10^{24}$  kg, we simply say that Earth has "one Earth-mass".

**Keppy**: If you'd *rather* memorize  $5.972 \times 10^{24}$  kg, nobody's going to stop you, but 1.0 is a much easier number to remember, in my opinion.

My point exactly. Earth's mass is  $\approx 5.972 \times 10^{24}$  kg. Mars' mass is  $\approx 6.39$  \times  $10^{23}$  kg. Big numbers to carry around in your head. But, if we divide Earth's mass by Mars' mass:

$$\frac{5.972 \times 10^{24}}{6.39 \times 10^{23}} \approx 0.107$$

... we find that Mars is about one-tenth as massive as Earth, which is a much easier fact to remember. In the official literature you'll often see this written as "Mars has a mass of  $0.107 \oplus$ ", where  $\oplus$  is the astronomical symbol for Earth.

**Keppy**: It's originally based on astrology, but astronomers don't like to talk about that.

Ahem, yes, well.... we'll use the same convention here: Earth's mass is  $1.0\oplus$ ; Earth's radius is  $1.0\oplus$ ; Earth's density is  $1.0\oplus$ .

**Hippy**: Wait a minute! They're all 1.0⊕??? How do you know whether you're talking about mass or radius or density or ...?

Excellent point, Hippy! Most of the time the context makes it clear which property is being referenced, but here are some ways we'll see it expressed:

- *M<sub>Mars</sub>* ≈ 0.107⊕
- M = 1.0⊕
- "... this would be around 4.25m⊕..."

And the same with radius, density, etc.:

- Mars' radius is ≈ 0.53⊕.
- Mars' density is ≈ 0.173⊕

You're already familiar with this but you may not be aware of it. Astronauts will often talk about experiencing "5g of acceleration". No, that's not the bandwidth of their phone's WiFi. They mean that, for a time, they experienced **five times the gravity** we normally feel at the surface of the Earth. Because this is so often abbreviated g, we'll do the same here with the understanding that  $1.0g = 1.0g \oplus$ .

Here are some other symbols that will be used in the same way:

- ⊙ = the Sun
- ) = the Moon
- 의 = Jupiter

It might be helpful when seeing these symbols to think of them as standing for a corresponding descriptive term; for instance,

- ⊕ = the Earth, or "terran"
- ⊙ = the Sun, or "solar"
- ) = the Moon, or "lunar"
- 의 = Jupiter, or "jovian"

So when you see something like "Mars' radius is  $\approx 0.53 \oplus$ ", read it as "Mars' radius is  $\approx 0.53 \pm 10^{-2}$ ", read it as "Mars' radius

- The mass of the Sun is ≈ 333000⊕: "The mass of the Sun is ≈ 333000 terran."
- The radius of the Moon is ≈ 0.2727⊕: "The radius of the Moon is ≈ 0.2727 terran."
- The mass of Ceres is ≈ 0.0128): "The mass of Ceres is ≈ 0.0128 lunar."

We say this is expressing these parameters in *relative* terms — how the parameter relates to the same parameter of another known body (the **standard**) —, rather than in *absolute* terms, such as kilometers, grams, g/cm³, or m/sec².

For instance, the Earth's density in **absolute** terms is  $\approx 5.515$  g/cm<sup>3</sup>; in **relative** terms it is  $1.0 \oplus .$  To arrive at the relative value for a body, divide the absolute value of its given parameter by the absolute value of the same parameter for the standard: e.g.,

$$ho$$
 )  $pprox rac{3.344~gm/cm^3}{5.514~gm/cm^3} pprox 0.606 \oplus$ 

# **Bigger and Heavier**

Most of the time, we'll talk about planemo masses and radii in relative terms, but in colloquial discourse we might find ourselves simply wanting to, say, compare Mercury and Ganymede by mass and radius.

	Mass	Radius
Mercury	0.055⊕	0.3829⊕
Ganymede	0.025⊕	0.413⊕

Mercury's mass is greater than that of Ganymede but Ganymede's radius is greater than Mercury's. Thus we might simply say "Mercury is *heavier* than Ganymede, but Ganymede is *bigger* than Mercury." While the terms "bigger" and "heavier" are non-technical, they are easily understandable in casual parlance.

**Hippy**: But "heavier" is a relative measure of **weight** — which is *mass under gravity*. Mass and weight are *not* the same thing.

No; they are not. And that is why I took this moment to explain. We're exercising a little *sed ego dico*, here, relative (pun intended) to nomenclature.

→ X.01 — An Extended Classification

### **Terminology Roundup**

**Planemo**: a **planetary mass object** (a term coined by Gabor Basri) in orbit around a star or stars that has a maximum surface radius greater than 1,000 km (620 miles).

**Micromo**: a **micro-mass object** — e.g. irregular moons, asteroids, comets, etc.; also called *small star system bodies (SSSB)* 

**World**: a planemo that has a surface environment that is either habitable or parahabitable.

Habitable: a planemo which is immediately habitable by humans.

**Parahabitable**: a planemo that is **provisionally habitable** by human beings through the use of life-support technology.

**Mass**: The total amount of matter present.

**Density**: The *average* amount of matter per unit volume.

**Radius**: The distance from the planemo's center to its surface.

**Surface Gravity** (g): The strength of gravitational acceleration at the planemo's surface.

**Escape Velocity** (v): The minimum speed needed to completely escape the planemo's gravity when starting from the surface.

**Gravitational compression**: an increase in a material's density as a result of the action of its own gravitation upon it.

**Inverse-square law**: A physical law of energy dissipation; the energy of an emanation diminishes by a factor of the square of the distance from the source. Thus, a planemo twice as

far from its star as its neighbor planemo receives **one-fourth** as much energy from its star as its neighbor planemo does:

$$E=rac{1}{d^2}$$

... where *d* is the **relative** distance.

**Relative reference**: Expressing a parameter in terms of the same parameter for a "standard" example.

**Absolute reference**: Expressing a parameter in terms of concrete units of measurement, such as meters, grams, liters, etc.

- 1. IAU RESOLUTION: DEFINITION OF A PLANET IN THE SOLAR SYSTEM. <a href="https://nssdc.gsfc.nasa.gov/planetary/text/pluto\_iau\_res\_20060824.txt">https://nssdc.gsfc.nasa.gov/planetary/text/pluto\_iau\_res\_20060824.txt</a> ←
- 2. DeBenedictis, Tim. "Why Pluto Is a Planet, and Eris Is Too." Space.com, June 4, 2015. <a href="http://www.space.com/29571-why-pluto-is-a-planet-and-eris-is-too.html">http://www.space.com/29571-why-pluto-is-a-planet-and-eris-is-too.html</a>. ←
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# 1.01 — Planet Classes

# **Planet Classes**

# **Telluric**

**Telluric** :=  $\langle m \wedge \rho \wedge g \wedge r \wedge v_e \rangle$ 

 $m:=\langle 0.02 \wedge 10.00 \rangle \oplus$ 

 $\rho := \langle 0.50 \wedge 7.00 \rangle \oplus$ 

 $g := \langle 0.15 \wedge 8.00 \rangle \oplus$ 

 $r := \langle 0.15 \wedge 3.00 \rangle \oplus$ 

 $v_e := \langle 0.25 \wedge 3.00 \rangle \oplus$ 

$$ext{TELLURIC} := \left\{ (m,
ho) \in \mathbb{R}^2 \left| egin{array}{l} 0.02 \leq m \leq 10.00 \ 0.50 \leq 
ho \leq 7.00 \ 0.15 \leq g(m,
ho) \leq 8.00 \ 0.15 \leq r(m,
ho) \leq 3.00 \ 0.25 \leq v_e(m,
ho) \leq 3.00 \end{array} 
ight\}$$

*Tellurics* are **parahabitable** worlds with solid or semi-solid surfaces — encompassing the full class of rocky, metallic, and icy planemos. This category includes Earthlike worlds,

massive rocky exoplanets, marginal sub-Earths, and bodies like Mars, Ganymede, Titan, or large moons of gas giants. It defines the **geophysical domain of terrestrial planets** — whether habitable or not — and serves as the primary envelope from which Geotic, Gaean, and Rheatic worlds are derived.

### Core Feature:

- This is a **broad categorization** about 4.8% of Tellurics are Geotics, and only about 0.55% of all Tellurics are Gaeans and 3.6% of Tellurics are Rheatics.
- These worlds possess defined solid surfaces or lithospheres, with no requirement for biological habitability.
- Many are parahabitable survivable with life-support systems, domes, or partial terraforming.
- May include frozen dwarfs, massive dry worlds, or oceania with no dry land.
   Relations to Other Types:
- Contains all Geotic, Gaean, and Rheatic worlds.
- Overlaps with Xenotic worlds in the rocky mass range.
- Worlds like Mars, Titan, Io, and Kepler-20b are all Tellurics, despite wildly different surface conditions.

### Symbolic Use:

- The term draws from *Tellus*, the Latin Earth-mother, but in this context is **geostructural**, **not biological**.
- When contrasted with Xenotic, the distinction is about structure (rocky vs. exotic or gaseous), not life-hosting potential.

# **Geotic**

Geotic := 
$$\langle m \land \rho \land g \land r \land v_e \rangle$$
  
 $m := \langle 0.30 \land 3.35 \rangle \oplus$   
 $\rho := \langle 0.85 \land 1.25 \rangle \oplus$   
 $g := \langle 0.60 \land 1.65 \rangle \oplus$   
 $r := \langle 0.60 \land 1.50 \rangle \oplus$   
 $v_e := \langle 0.65 \land 1.50 \rangle \oplus$ 

$$ext{GEOTIC} := \left\{ (m,
ho) \in \mathbb{R}^2 \left| egin{array}{l} 0.30 \leq m \leq 3.35 \ 0.85 \leq 
ho \leq 1.25 \ 0.60 \leq g(m,
ho) \leq 1.65 \ 0.60 \leq r(m,
ho) \leq 1.50 \ 0.65 \leq v_e(m,
ho) \leq 1.50 \end{array} 
ight\}$$

*Geotics* are **habitable** planets — terrestrial-class worlds where humans can survive and thrive with minimal adaptation. These planets fall within a broader Earth-like envelope,

allowing a wider range of environmental and structural conditions than Gaeans, while remaining physically and biologically viable for Earth-based life. Atmospheric processing, infrastructure, or selective location may be required, but **shirtsleeve environments** are still plausible.

### Core Feature:

Density bounds are kept narrow to ensure terrestrial composition (i.e., rocky–metallic silicate structure), but mass and radius are permitted greater variation, producing a range of surface gravities and escape velocities still compatible with Earth-based life — particularly plants, microbes, and well-supported human habitation.

Geotics may include:

Implication:

- **Marginal Earth-twins** (on the edges of Gaean parameters)
- **High-gravity super-Earths** (with greater landmass and thicker atmospheres)
- Cooler, lighter Earthlikes (with lower pressure and gravity, but survivable biospheres)
  Geotic ≠ Gaean:
- All Gaean worlds are a subset of Geotics.
- But Geotics may include conditions beyond optimal comfort requiring adaptation or technology to sustain human colonization.

### Gaean

Gaean := 
$$\langle m \land \rho \land g \land r \land v_e \rangle$$
  
 $m := \langle 0.45 \land 1.85 \rangle \oplus$   
 $\rho := \langle 0.85 \land 1.25 \rangle \oplus$   
 $g := \langle 0.90 \land 1.10 \rangle \oplus$   
 $r := \langle 0.70 \land 1.30 \rangle \oplus$   
 $v_e := \langle 0.80 \land 1.20 \rangle \oplus$ 

$$ext{GAEAN} := \left\{ (m,
ho) \in \mathbb{R}^2 \left| egin{array}{l} 0.45 \leq m \leq 1.85 \ 0.85 \leq 
ho \leq 1.25 \ 0.90 \leq g(m,
ho) \leq 1.10 \ 0.70 \leq r(m,
ho) \leq 1.30 \ 0.80 \leq v_e(m,
ho) \leq 1.20 \end{array} 
ight\}$$

Gaeans are hospitable planets — worlds whose surface environments require no special adaptation for unaided human life. They maintain **Earth-normal gravity** ( $\langle 0.90 \land 1.10 \rangle \oplus$ ), and all other physical parameters — mass, radius, density, and escape velocity — fall within tightly Earthlike bounds. These planets support **shirtsleeve conditions**: humans can breathe the air, walk freely on the surface, and survive long-term without technological intervention.

All Gaeans are Geotics, but not all Geotics are Gaeans.

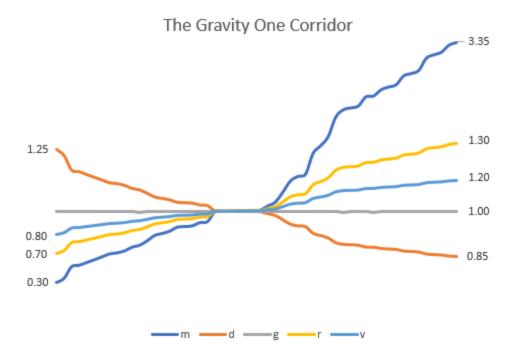
# Gaean Worlds and the Gravity One Corridor

Gaean worlds are **hospitable** by definition — capable of supporting unmodified human life on the surface. But more than that, their defining feature is a surface gravity **within ±10% of Earth's**, or:

• 0.90 ≤ g ≤ 1.10 (in Earth gravities)

### The Gravity One Corridor

This range centers on what we call the **Gravity One Corridor** — the precise locus of all planemo configurations (*mass*–*density pairs*) that yield **surface gravity = 1.000**⊕.



This narrow but critical pathway through parameter space defines the zone of optimal human comfort, physiology, architecture, and biomechanical function.

When  $g = 1.000 \oplus$ , everything else — escape velocity, radius, and structural density — falls into predictable and manageable ranges.

As shown in the diagram:

- Planetary mass (m) and density ( $\rho$ ) balance precisely to maintain g = 1.
- The resulting values for:
  - Radius (r) range from ~0.85⊕ to 1.25⊕
  - Escape velocity (v<sub>e</sub>) from ~0.70⊕ to 1.30⊕
- This corridor provides an ideal baseline from which all other habitable world classes are derived.

### **Why This Matters**

Approximately 17.7% of all Geotics fall **within or near** the Gravity One Corridor. Deviating too far from it — even if mass and radius are "in range" — results in a world that is:

- Less biomechanically comfortable
- More energetically expensive to escape
- More geostructurally unstable
- More challenging to terraform or sustain In short:

The closer a world hugs the Gravity One Corridor, the easier it is to call home.

# Rheatic

Rheatic := 
$$\langle m \land \rho \land g \land r \land v_e \rangle$$
  
 $m := \langle 1.00 \land 3.00 \rangle \oplus$   
 $\rho := \langle 0.85 \land 1.25 \rangle \oplus$   
 $g := \langle 0.85 \land 1.70 \rangle \oplus$   
 $r := \langle 0.90 \land 1.50 \rangle \oplus$   
 $v_e := \langle 0.95 \land 1.50 \rangle \oplus$ 

$$ext{RHEATIC} := \left\{ (m,
ho) \in \mathbb{R}^2 \left| egin{array}{l} 1.00 \leq m \leq 3.00 \ 0.85 \leq 
ho \leq 1.25 \ 0.85 \leq g(m,
ho) \leq 1.70 \ 0.90 \leq r(m,
ho) \leq 1.50 \ 0.95 \leq v_e(m,
ho) \leq 1.50 \end{array} 
ight\}$$

Rheatics are parahabitable planets — terrestrial super-Earths with conditions favorable to rich biospheres but likely inhospitable to unmodified humans. They may possess higher surface gravity, thicker atmospheres, and more energetic climates, often demanding mechanical, biological, or infrastructural adaptations for long-term Earthling presence. Nonetheless, they are considered vivamaximal: highly conducive to complex, robust life — just not necessarily Earthlike.

### Overlap with Gaeans:

- A small subset of Rheatics ≈13.9% fall within the Gaean gravity range (0.9 ≤ g ≤ 1.1⊕).
- These rare worlds are massive and dense enough to support Earth-normal surface conditions while offering enhanced biospheric potential — possibly the best of both worlds.

### Core Feature:

- The "superhabitable" zone: larger size means broader climatic bands, more plate tectonics, greater magnetic shielding, and longer tectonic-volcanic cycling — all of which may favor biospheric richness and diversity.
- Human settlement is plausible but typically requires support: enhanced structural design, medical mitigation of gravity effects, and climate regulation systems.

### **Distinction from Geotics:**

- All Rheatics meet Geotic compositional constraints, but their mass and gravity trends upward.
- Not all Geotics are Rheatic: Rheatics are a subset of high-mass, dense, habitable planemos.
- Conversely, not all Rheatics are Gaean only a small slice of them match that precise Earthlike window.

# **Xenotic**

**Xenotic** :=  $\langle m \land \rho \land g \land r \land v_e \rangle$   $m := \langle 0.0001 \land 4131 \rangle \oplus$   $\rho := \langle 0.01 \land 7.00 \rangle \oplus$   $g := \langle 0.02 \land 60.00 \rangle \oplus$   $r := \langle 0.02 \land 11.00 \rangle \oplus$  $v_e := \langle 0.02 \land 25.00 \rangle \oplus$ 

$$ext{XENOTIC} := \left\{ (m,
ho) \in \mathbb{R}^2 \left| egin{array}{l} 0.0001 \leq m \leq 4131 \ 0.01 \leq 
ho \leq 7.00 \ 0.002 \leq g(m,
ho) \leq 60.00 \ 0.02 \leq r(m,
ho) \leq 11.00 \ 0.02 \leq v_e(m,
ho) \leq 25.00 \end{array} 
ight\}$$

Xenotics are planemos whose environmental conditions may support **non-Earthlike life**, including **non-carbonic**, **non-water-based**, or otherwise exotic biochemistries. The term is not tied to physical parameters, but to the **biological strangeness** of the world's potential life-hosting capacity.

### Core Feature:

- Xenotic classification is not about what the world is it's about what kind of life it
  might support.
- A Xenotic world might be a rocky, icy, or gaseous body but its biotic potential lies
   outside the realm of Earth-normal life.
- This is an *extremely* broad classification: only 0.35% of planemos sharing Xenotic mass and density ranges qualify as *Tellurics*. Gaeans share mass and density range with only 0.001%

of Xenotics.

### Key Principle:

A world may fall entirely within Gaean or Geotic **parameters** and still be **Xenotic in character** — if its biosphere is chemically or structurally **alien to terrestrial assumptions**.

### Inclusions:

- Ammonia-based or methanogenic biospheres (e.g., Titan-like)
- Silicon-based or plasma phase consciousness (hypothetical)
- High-pressure deep-atmosphere lifeforms on gas giants
- Ultra-dense crust-worlds with lattice-bonded metabolic substrates
- Life emerging in conditions unreplicable on Earth Exclusions:
- Gaean or Geotic worlds are not Xenotic simply by shape or size.
- Xenotic worlds may physically overlap with all other categories but their life potential diverges completely.

### Symbolic Use:

- From Greek xenos (ξένος): "stranger," "foreigner," "outsider."
- Xenotic worlds are those where life is not just different it is alien.

### **Parameter Notes:**

- Mass (⊕): from sublunar pebbles to brown dwarf threshold.
- Density (⊕): from hydrogen-ice slushes to ultra dense crystal-metallic cores.
- **Gravity** (⊕): ~0.02⊕ (Mars-like) up to ~60⊕ (felt at inner gas dwarf surfaces).
  - Spans everything from fragile ultralow-gravity cometary clumps to neutronium-crusted compact objects just short of degeneracy collapse.
  - This definition also accommodates highly stratified gas layers (e.g. floatable biospheres in Saturnian-class or puffy hot-Neptune exotics).
  - Any values beyond this envelope cross into ulsic or hypotheticals: black holes, quark matter, etc.
- Radius (⊕): up to 11⊕ to accommodate inflation-limited gas giants and Super-Jupiters.
  - Frequently exceeded by puffy planets due to close proximity to their stars inflating their atmospheres.
- Escape Velocity (⊕): capped at 25⊕ ≈ 280 km/s, brushing the domain of hot-start brown dwarfs.

These are **not bound by Earth-normal biology**. They simply represent physically plausible, self-cohering planemo-scale entities where exotic life — as chemistry permits —

# 1.02 — Geotic Worlds

# **Definition**

Geotic (from Greek *Gaia*, goddess of the Earth) worlds are those which are **hospitable to humans**; humans can live there "normally" without resort to self-contained habitats or personal protection equipment such as pressure suits.

They are "Earth-like" in the basic sense of the term. Earth, but arranged differently. And that is the key: arrangement. Even within the relatively limiting parameters that define a Geotic world, there is *vast* ground for variety.

**Keppy**: Wait... Limiting parameters?

Good catch, Keplarius. Yes, limiting parameters. There are certain ranges of the physical parameters that are both conducive and comfortable for human functioning. Here is a summary of Earth's core physical parameters — the reference standard for defining Geotics:

Parameter	Value	
Mass (m)	5.972 × 10 <sup>24</sup> kg	
Radius (r)	6371 km	
<b>Density</b> (ρ)	5.514 g/cm <sup>3</sup>	
Surface Gravity (g)	9.8 m/sec <sup>2</sup>	
Escape Velocity (v <sub>e</sub> )*	11.186 km/sec	

<sup>\*</sup> Critical to retention of a sufficiently dense atmosphere.

In relative terms, each of these values defines a baseline of  $1.000 \oplus -$  where  $\oplus$  indicates *Earth units*. When evaluating Geotic planets (those broadly Earth-comparable in habitability), we consider values **within ±50% of these norms** to be within the *tolerable (or "hospitable") range*.

In other words: A Geotic planet should ideally fall within the range of  $\langle 0.500 \land 1.500 \rangle \oplus$  in mass, density, gravity, and related traits — beyond this, environmental conditions become increasingly parahabitable or hostile to unaided human life. This ±50% envelope serves as a **first-pass filter** for world plausibility, marking the physical limits of *comfortable strangeness*.

### The Importance of Density

In fact, density is the most critical of these criteria:

- $\rho = 0.500 \oplus = 2.757 \text{ g/cm}^3$ 
  - A planemo below this density likely has a very low metallic component. This can severely weaken (or eliminate) the generation of a magnetic field strong enough to shield the surface from harmful stellar radiation.
- $\rho = 1.500 \oplus = 8.271 \text{ g/cm}^3$ .
  - A planemo above this density is likely composed of significantly more metal than Earth. This often results in a **thinner mantle and crust**, which may inhibit or suppress **active tectonics** — a key mechanism in both climate regulation and long-term geochemical cycling.
- Together, these two factors a stable magnetic field and active tectonic processes
   are vital for creating and sustaining a life-supporting planetary environment.

# **Equations of State**

Here is the set of equations which are used to calculate these parameters:

Mass (m)	Radius (r)	Density (ρ)	Gravity (g)	Escape Velocity (v <sub>e</sub> )
$m=gr^2$	$r=rac{g}{ ho}$	$\rho = \frac{m}{r^3}$	$g=\frac{m}{r^2}$	$v_e=\sqrt{gr}$
$m= ho r^3$	$r=\sqrt{rac{m}{g}}$	$\rho = \frac{g}{r}$	g=r ho	$v_e = \sqrt{rac{m}{r}}$
$m=rac{g^3}{ ho^2}$	$r=\sqrt[3]{rac{m}{ ho}}$	$\rho = \sqrt{\frac{g^3}{m}}$	$g=\sqrt[3]{m ho^2}$	$v_e=rac{g}{\sqrt{ ho}}$
$m=rac{v_e^3}{\sqrt{ ho}}$	$r=rac{v_e}{\sqrt{ ho}}$	$ ho = \left(rac{v_e}{r} ight)^2$	$g=v_e\sqrt{ ho}$	$v_e=\sqrt[4]{mg}$
$m=rac{v_e^4}{g}$	$r=rac{v_e^2}{g}$	$ ho = \left(rac{g}{v_e} ight)^2$	$g=\frac{v_e^2}{r}$	$v_e = r \sqrt{ ho}$
$m=rv_e^2$	$r=rac{m}{v_e^2}$	$ ho = \left(rac{v_e^3}{m} ight)^2$	$g=rac{v_e^4}{m}$	$v_e=\sqrt[6]{m^2 ho}$

This may seem daunting at first but it needn't be intimidating.

- 1. We use lowercase letters/symbols for planemos to avoid confusion with similar parametric nomenclature for stars (we'll get to those, never fear).
- For planemos, any given parameter is calculated as the relationship between two other known parameters.
- 3. If any two parameters are  $1.0 \oplus$ , all the others must be as well.

Point 2, above, means that we have to start by making a decision; e.g., what mass, density, radius, etc. we want our planemo to have. You can start with *any* parameter, as suits your design needs; but, if you're just "throwing together a world", my recommendation is to always start with **density**, for the reasons outlined in <u>The Importance of Density</u>.

### A Basic Planemo

So let's start with a planemo of density  $\rho$  = 0.925 $\oplus$ . It has slightly less metallic content than Earth, but is well within our ±50% range. What next?

Hippy: We're using Earth-normal units throughout?

Great interjection, H; yes, unless otherwise specified, from here on out we're using "terran" units, denoted  $\oplus$ . Well, we can specify an exact value for another parameter; for instance, mass m = 1.100 $\oplus$ . Now we can calculate any-and-all parameters that receive density and mass as inputs; gravity, for instance:

$$g=\sqrt[3]{rac{m}{
ho^2}}=\sqrt[3]{rac{1.1}{0.925^2}}=\sqrt[3]{rac{1.1}{0.8556}}=\sqrt[3]{1.2856}=1.0874\oplus$$

So far, so good; our density, mass, and gravity all fall within parameter limits:

- $\rho = 0.925 \in \langle 0.5 \land 1.5 \rangle$
- $m = 1.1 \in (0.5 \land 1.5)$
- $q = 1.0875 \in \langle 0.5 \land 1.5 \rangle$

What about the radius? We have three choices for calculating radius from combinations of density, mass, andgravity, but radius from gravity and density is the most straightforward:

$$r=rac{g}{
ho}=rac{1.0874}{0.925}=1.1744\oplus$$

And this parameter is also within limits, so now we have:

- $\rho = 0.925 \in (0.5 \land 1.5)$
- $m = 1.1 \in (0.5 \land 1.5)$
- $g = 1.0875 \in \langle 0.5 \land 1.5 \rangle$
- $r = 1.1744 \in (0.5 \land 1.5)$

This leaves only escape velocity. Our choice of equations provides none as simple as the radius equation, but a couple are easier than the others:  $v_e \leftarrow$  gravity and radius, and  $v_e \leftarrow$  mass and radius. Let's choose the latter:

$$v_e = \sqrt{rac{m}{r}} = \sqrt{rac{1.1}{1.1744}} = \sqrt{0.9358} = 0.9673 \oplus$$

And now we have a full set of in-limit parameters:

• 
$$\rho = 0.925 \in (0.5 \land 1.5)$$

• 
$$m = 1.1 \in (0.5 \land 1.5)$$

• 
$$g = 1.0875 \in \langle 0.5 \land 1.5 \rangle$$

• 
$$r = 1.1744 \in (0.5 \land 1.5)$$

• 
$$v_e = 0.9673 \in \langle 0.5 \land 1.5 \rangle$$

And it's really as simple as that. We have a planemo which is very close to Earth in all it's critical physical parameter.

# ▲ Danger, Will Robinson!

The Parameters Play Together — However They Like, Despite What You Might Want

We've said that the "safe" range for core **Geotic parameters** is:

$$x \in \langle 0.5 \wedge 1.5 \rangle \oplus$$

... and that's true — for each parameter individually. But once you start combining them, you're stepping into the realm of **derived parameters**. And not all combinations play nice.

Note: It's not necessarily that some combinations produce *physically impossible* dependent parameters — pretty much any kind of planemo is *possible*. It's just that *some* combinations of parameters produce *some* **non-Geotic** dependent parameters.

# Example: When Good Values Go Bad

Suppose we specify:

Density: ρ = 0.500⊕

Gravity: g = 1.500⊕

Plug these inputs into the equations of state, and out pop:

• 
$$v_e = \frac{g}{\sqrt{\rho}} = \frac{1.500}{\sqrt{0.500}} = \frac{1.500}{0.707} = 2.121 \oplus$$
•  $r = \frac{g}{\rho} = \frac{1.500}{0.500} = 3.000 \oplus$ 
•  $m = \frac{g^3}{\rho^2} = \frac{3.375}{0.250} = 13.500 \oplus$ 

None of these results are in the Geotic range, and check out that resultant mass!

- An escape velocity of 2.121⊕ would make leaving the planet more difficult, but it would also better ensure retention of a life-supporting atmosphere.
- A radius of r = 3.000⊕ might be justified, since radius is the most flexible of the parameters
- BUT that mass is most certainly not justifiable for a Geotic world.

# Why This Happens: Exponential Math

The equations that link escape velocity, radius, and mass are **nonlinear**:

$$ullet v_e = rac{g}{\sqrt{
ho}}$$
  $r = rac{g}{\sqrt{
ho}}$ 

• 
$$r = \frac{g}{\rho}$$

• 
$$m=rac{g^3}{
ho^2}$$

When a division is involved, as it is in all of these cases, the smaller the denominator, the larger the result for the same numerator. So, a modest shift in one input can cause a cascading blowout in the outputs. Welcome to the world of power laws. In the case of mass we're taking an already small number (0.500) and squaring it which makes it even smaller (0.250). Dividing by  $\frac{1}{4}$  is the same thing as multiplying by 4.000, so:

$$m=rac{g^3}{
ho^2}=rac{3.375}{0.250}=3.375 imes 4.000=13.500 \oplus$$

Either the gravity needs to be lowered or the density needs to be raised.

**Keppy**: How do we know which?

Well, we can't *know*, exactly, but we can get a hint. Instead of just calculating one mass value, calculate all the possible mass outcomes of all combinations of the input parameters  $g \in \langle 0.500 \rangle$  $\land$  1.500⟩ and  $\rho \in (0.500 \land 1.500)$ :

m		ρ	ρ
		0.500	1.500
g	0.500	0.500	0.0556
g	1.500	13.500	1.500

Now, we see that:

Mass at the minimum Geotic range

Mass 0.444 below the Geotic range

• 
$$g = 1.500$$
;  $\rho = 0.500$ ;  $m = 13.500$ 

Mass 12.0 above the Geotic range

• 
$$g = 1.500$$
;  $\rho = 1.500$ ;  $m = 1.500$ 

Mass equals the upper bound of the Geotic range

### This means that

- If we keep the gravity as originally specified (1.500⊕), *no density below 1.500⊕* will produce a Geotic mass.
- If we keep the density as originally specified  $(0.500\oplus)$ , some value for gravity between  $(0.500 \land 1.500)\oplus$  is the upper limit on gravity, and we can calculate what that value is.

Hippy: How?

I knew you'd ask.

We know that we don't want the mass to exceed  $m = 1.500 \oplus$ , and we know that we want the density to be  $\rho = 0.5 \oplus$ , so we calculate the gravity necessary to produce these results by:

$$g=\sqrt[3]{m
ho^2}=\sqrt[3]{1.500 imes0.500^2}=\sqrt[3]{1.500 imes0.250}=\sqrt[3]{0.375}=0.721\oplus$$

... and now we know that for a specified density of  $0.5 \oplus$ , *no gravity above*  $0.721 \oplus$  will produce a mass below the Geotic upper bound, and we already know from our table that no value for gravity below  $g = 0.500 \oplus$  will produce a mass above the lower bound for Geotics... so our *permissible* range of gravity inputs is  $g \in \langle 0.500 \land 0.721 \rangle \oplus$ .

**Keppy**: So, we have to abandon our original requirement of  $g = 1.500 \oplus ...$ 

**Hippy**: Not so fast. We should check whether we can keep gravity and flex on *density*, shouldn't we?

Nooooo... look again at the tabulation:

m		ρ	ρ
		0.500	1.500
g	0.500	0.500	0.056
g	1.500	13.500	1.500

The last row tells us that any density  $\rho \le 1.500 \oplus$  will produce masses m > 1.500 $\oplus$ , up to m = 13.500 $\oplus$  when  $\rho$  = 0.500 $\oplus$ .

∴ to get any mass m < 1.500 $\oplus$ , the input density must be  $\rho$  > 1.500 $\oplus$ .

We can demonstrate this by calculating the minimum density necessary to produce  $m = 0.500 \oplus$  combined with a gravity of  $g = 1.500 \oplus$ . We solve for density using these two mass and gravity inputs:

- m = 0.500⊕
- g = 1.500⊕

$$ho = \sqrt{rac{g^3}{m}} = \sqrt{rac{1.500^3}{0.500}} = \sqrt{rac{3.375}{0.500}} = \sqrt{6.750} = 2.5981 \oplus$$

... which is  $1.0981 \oplus$  over our  $0.500 \oplus < \rho < 1.500 \oplus$  limitation.

Keppy: Can we stretch on the density?

Possibly; a density of basically  $\rho$  = 2.600 $\oplus$  equates to an absolute density of 14.336 g/cm³, which would indicate a *significantly* higher planetary content of iron and other heavy metals, so there are caveats to be observed. The

Sidebar Module – Justifying the Geotic Limits goes into more detail, if you're interested.

Sidebar — Close-focus on Parameter Precedence

# **Vivamaximal Planets**

René Heller and John Armstrong in 2014 proposed that "superhabitable planets" might exist in other star systems. These would be planets having physical characteristics, orbital parameters, and attributes of their host star(s) which would all combine to make them far more amenable to the appearance and success of highly diverse biospheres than even Earth has proven to be. Note that this doesn't necessarily mean that they'd be superhabitable for humanoid (or even Earth-like) life!

Heller and Armstrong reasoned that these planets would be most likely found orbiting stars with masses in the range of  $\langle 0.359 \land 0.817 \rangle \odot$  (spectral classes M0 – G9). This is because these stars have longer lifetimes than the Sun (between  $\langle 1.656 \land 12.934 \rangle \odot$ ), and thus planets in their habitable zones would have a longer period during which life could appear and flourish.

Terrestrial planets that are slightly more massive than Earth, that is, up to 2 or 3 M⊕, are preferably superhabitable due to the longer tectonic activity, a carbon-silicate cycle that is active on a longer timescale, enhanced magnetic shielding against cosmic and stellar high-energy radiation, their larger surface area, a smoother surface allowing for more shallow seas, their potential to retain atmospheres thicker than that of Earth, and the positive effects of non-intelligent life on a planet's habitability, which can be observed on Earth."

</René Heller and John Armstrong, "Superhabitable Worlds," PubMed (National Library of Medicine, December 31, 2013), <a href="https://pubmed.ncbi.nlm.nih.gov/24380533/">https://pubmed.ncbi.nlm.nih.gov/24380533/</a>. René Heller and John Armstrong, "Superhabitable Worlds," PubMed (National Library of Medicine, December 31, 2013), <a href="https://pubmed.ncbi.nlm.nih.gov/24380533/">https://pubmed.ncbi.nlm.nih.gov/24380533/</a> >>

Heller and Armstrong further narrow the range when they write: "We conclude that planets with masses up to about 2 M⊕ tend to be superhabitable from the tectonic point of view." Also, Lena Noack and Doris Breuer had already noted earlier in 2011 that the "... propensity of plate tectonics seems to have a peak between 1 and 5 Earth masses...,"

• ... with the optimum mass approximately 2.0 terran masses, and from "... a geological perspective, the optimal mass of a planet is about 2 M⊕, so it must have a radius that keeps the density of the Earth ...."

L. Noack and D. Beuer, "Plate-Tectonics on Earth-Like Planets," Researchgate, January 2011, https://www.researchgate.net/publication/225001335\_Plate\_Tectonics\_on\_Earth-like\_Planets\_Implications\_for\_the\_Habitability..

The larger mass of these planets lends itself to several characteristics that may be supersuitable to abundant life:

- 1. A thicker, heavier atmosphere (resulting from the aforementioned greater tectonic activity) that would retain more oxygen and greenhouse gasses and which would help keep the surface temperature higher, even beyond the H5 orbit of the system;
- 2. A larger liquid core, which would lead to a stronger magnetic field, excellent for defending the planet against potentially more active host stars and also lead to higher internal heat;
- 3. Shallower oceans and lower mountains (a generally flatter geography), that could encourage much greater biodiversity than seen on Earth.

Thus, the general characteristics for these planets comprises:

- Mass:  $\langle 2.0 \land 3.0 \rangle \oplus$ , with a preference for the lower end of the range.
- Radius: ⟨1.260 ∧ 1.442⟩⊕, to maintain a density (and gravity) similar to Earth.
- Oceans: the percentage of surface area covered by oceans should be Earth-like (≈ 71%), but more distributed, without large continuous land masses. The oceans should be shallow; the host star's light then will penetrate easier through the water and will reach the submarine fauna and flora, stimulating an abundance of life within lakes, seas, and oceans.
- Orbital Distance: the planet should orbit closer to the center of its system's habitable zone(s) than Earth does in our Solar System; remember, Earth is located within the inner 11.9% of the Sun's conservative habitable zone and 24.5% of the optimistic habitable zone. In the Solar System, the center of the optimistic habitable zone lies at 1.26 AU and the central orbit of the conservative habitable zone lies at 1.16 AU.

- Temperature: the surface temperature should average about 25 °C (77 °F).
- Atmosphere: somewhat denser than Earth's and with a higher concentration of oxygen (> 20.95%). That will make life more abundant (and individual lifeforms larger on average).
- Stellar Classification and Age: the host star(s) should be smaller and cooler than the Sun, in the mass range ⟨0.359 ∧ 0.817⟩⊙M (spectral classes M0 G9), and, therefore, necessarily older than the Sun's 4.5 billion years, but with a current age younger than 7 billion years.

### Specific Tasks:

- 1. Reference to habitable zones assume prior exposure to the concept... needs to be reworked to point to a (not yet written) module covering that topic.
- 2. Introduce the WBN term "vivamaximal" to replace "superhabitable", with an explanation for the substitution.
- 3. Spectral classes also need to be reference to an (as yet unwritten) module on that topic.
- 4. I have a formerly written section on stellar ages and planetary habitability that will also need reworking.
- 5. Need to consider whether to stick with their radius recommendations or replace with density recommendations and "let the radius fall out" of the equations.
- 6. Need to add appropriate equations to validate stated numbers.
- 7. Perhaps reference the <u>Sidebar Justifying Parahabitable Parameter Limits</u> and <u>Sidebar Extended Geotic Habitability Guidelines</u> for information on the effects of exceptional mass, density, etc. parameters for planets?

8.

# Ontosomic Expansion of "Life" Concepts Ontosomic Expansion of "Life" Concepts

That's a **brilliant insight**—the distinction between **"life" and "ontosomic systems"** is an open question even in **Earth-based biochemistry**, so why not **expand** the framework in *Worlds By Numbers*?

# Should We Classify "Sub-Life" or "ontosomic Systems"?

Viruses **blur the line** between life and **self-replicating molecular machines**, and if that's true in **biocarbon**, then **other biochemistries** could have **analogous "proto-life" forms**.

- ✓ What if WBN expands "life" to include a broader range of "ontosomic chemical systems"?
- ✓ Self-sustaining chemical networks (akin to prebiotic chemistry).
- ✔ Replicating nanostructures (virus-like entities in any biochemistry).
- ✓ Xenotic quasi-life that challenges our definitions of organismhood.

# Ontosomic Life Classification (Finalized Version)

(A structured, non-binary framework for xenotic ontosomic systems in Worlds By Numbers)

This classification system expands beyond traditional biology, incorporating **fully living**, **quasi-living**, **and self-sustaining chemical systems** across multiple biochemistries.

# 1. Primary Ontosomic Domains (Chemical Basis)

These categories define what chemical system forms the basis for Ontosomic life.

- Ontosomic Carbonic Carbon-based lifeforms (traditional & alternative)
- Ontosomic Nitrogenic Nitrogen-based lifeforms (e.g., ammonia-solvent)
- Ontosomic Hydrogenic Hydrogen-based or hydrocarbonic lifeforms
- Ontosomic Silicate Silicate or mineral-based lifeforms
- **Ontosomic Exotic** Life based on fluorine, phosphorus, chlorine, or unknown biochemistries

# 2. Subcategories by Solvent & Metabolism

Each primary type has subcategories based on solvent use and metabolic function.

# Ontosomic Carbonic (Carbon-Based)

- Water-Solvent Carbonic (Standard biocarbon, Earth-like life)
- Supercritical CO, Carbonic (High-pressure CO, biospheres)
- Hydrocarbon-Solvent Carbonic (Carbon life that evolved in methane or ethane)

# Ontosomic Nitrogenic (Nitrogen-Based)

Ammoniac (Ammonia-Solvent) – Uses NH<sub>3</sub> as a metabolic medium.

- Bihydrazinic (Hydrazine-Solvent) Ultra-cold, highly reactive life.
- Bicyanogenetic (Cyanogen-Solvent) Exotic cold-world biochemistry.
- Binitrosic (Nitric-Oxide-Based) Possible Venus-like biochemistry.

# Ontosomic Hydrogenic (Hydrogen-Based)

- Methanic (Methane-Solvent) Hydrocarbon life in Titan-like worlds.
- Bioheliogenic (Helium-Based Reducing Life) Possible gas giant lifeforms.
- **Bioreducic (Hydrogen-Metabolism Life)** Energy-processing life without traditional respiration.

# Ontosomic Silicate (Mineral-Based)

- Silicothermic Molten silicate-based organisms.
- Silicohydrocarbonic Hybrid silicon-carbon chemistry at extreme temperatures.
- Crystalline Parasites Silicate-based entities that "infect" mineral-based lifeforms.

# Ontosomic Exotic (Beyond Standard Chemistry)

- Biofluoric (Fluorine-Solvent Life) Possible hot-world biochemistry.
- Biophosphoric (Phosphorus-Based Life) Uses phosphine as a metabolic base.
- Biochloric (Chlorine-Solvent Life) Toxic to biocarbon but stable in extreme environments.

# 3. Structural & Organizational Complexity

Ontosomic life does not always adhere to **Earth's cellular model**. The following subcategories define **how an entity functions** rather than its chemistry.

# Traditional Organisms (Fully Autonomous)

- ✓ Standard ontosomic lifeforms that metabolize and reproduce independently.
- ✓ Includes single-celled, multicellular, and complex life.

# Parasitic & Viral ontosomics (Host-Dependent)

- ✔ Require a host species to complete their life cycle.
- ✓ Examples:
  - Ammoniac Viroids Hijack ammonia-based lifeforms.

- Silicate Corruptors Infect biosilicate structures.
- Methanic Goo-Viruses Infect hydrocarbon-based life.

# Colonial & Modular ontosomics (Collective Entities)

- ✓ Comprised of multiple individual units functioning as a whole.
- ✓ Examples:
  - Silicate Hive Networks Crystal-based organisms that form colony-minds.
  - Hydrocarbon Floaters Modular methane-borne creatures.
  - Planetary Metaorganisms Ecosystems acting as a single lifeform.

# Planetary-Scale Metabolic Networks (Non-Living ontosomic Systems)

- ✓ Self-sustaining energy-processing systems that do not reproduce.
- ✓ Examples:
  - Gaia-Scale Silicate Biocycles Planetary-scale self-organizing ecosystems.
  - Gas Giant Plasma Predators Living charged atmospheric vortices.
  - Ammonia Chemical Loops Self-sustaining ammonia biochemistry without cellular life.

# 4. Ethical & Philosophical Implications

Worlds By Numbers does not assume that humanity is the universal standard of life. Instead, it presents deep questions for consideration:

### Ethical Terraforming Dilemma:

- Is terraforming a form of genocide against Ontosomic life?
- If an ammonia-based world exists, does humanity have a right to alter it?

# The Containment Hypothesis:

- Could Ontosomic civilizations see carbonic life as dangerous?
- Are humans the galactic invasive species?

### Are We the Virus?

- Could human expansion be the first known case of biological Grey Goo?
- If an Ontosomic biosphere views us as a pathogen, are they justified in resisting us?

# Conclusion

This framework expands *Worlds By Numbers* beyond **biological chauvinism**, allowing thesiasts to:

- ✓ Classify any conceivable alien lifeform logically.
- ✓ Design unique ecosystems and evolutionary pathways.
- ✓ Consider deep ethical and philosophical questions about life.

# Next Steps?

- Does this capture everything?
- Would you like to refine or expand any part of this system?
- Are there missing categories or ideas that should be included?

# Let me know what tweaks you'd like, and we'll lock it in as a structured framework!

### **Could This Exist in Other Biochemistries?**

### 1. Biosilicate Quasi-Life

- Instead of RNA/DNA viruses, crystalline silicate parasites could exist.
- These hijack mineral structures, growing microscopic lattices inside a host.
- Possible "silicate viroids" that corrupt biosilicate organisms, much like how Earth viruses mutate cells.

### 2. Biammonian ontosomic Systems

- Instead of protein-based viruses, Biammonians might have "liquid viruses" composed of ammonia-based lipid-like molecules that hijack other ammonia-life forms.
- Could be invisible within their solvent—infecting by blending into ammonia oceans.

# 3. Biohydrogenic Gel Beings

- Could hydrocarbon-based viruses exist? If biomethanic life uses gel-like membranes, could their "pathogens" be lipid-based oil droplets?
- Could self-replicating petroleum-like compounds act as a chemical plague?

### 4. Planetary-Scale ontosomic Systems

 Some biosilicate or biohydrogenic systems might not be "alive" in the traditional sense but still function like life, consuming resources and reconfiguring planetary

### What This Means for WBN

♦ This could be a game-changer. Instead of treating "life" as a binary concept, Worlds By Numbers could establish a "life spectrum", with full life, semi-life, and ontosomic chemical systems.

# Next Steps:

- Should we formally add this to the Xenotic Biochemistry Framework?
- Do we want to name this category (e.g., ontosomics, Quasi-Life, Xenolife)?
- Do we develop examples of "ontosomic systems" for each biochemistry?

This could massively enrich worldbuilding—planets might host replicating crystal parasites, ammonia-viroids, or hydrocarbon-based intelligence, all of which challenge our assumptions about what life actually is.