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[1], 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[2] at *Space.com*, argues for a much simpler planetary cutoff: any body more than about 1,000 km in radius, orbiting its star on its own, will — no matter whether it’s made of rock, ice, or metal — inevitably take on a nearly spherical form under its own gravity.

From this perspective, his definition trims away most of the IAU’s complexity:

1. A **planet** is a celestial body that (a) orbits the Sun, and (b) has a surface radius exceeding 1,000 km (620 mi).
2. All other objects in solar orbit, apart from satellites, are classed 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***[3] 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,
2. 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 ≈ 5.972 × 10^{24} kg, we simply say that Earth has "one Earth-mass".

> **Keppy**: If you'd *rather* memorize 5.972 × 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 ≈ 5.972 × 10^{24} kg. Mars' mass is ≈ 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⊕", where ⊕ 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⊕; Earth's radius is 1.0⊕; Earth's density is 1.0⊕ —

> **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_{Mars} ≈ 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⊕.

Here are some other symbols that will be used in the same way:

- ⊙ = the Sun
- ☽ = the Moon
- ♃ = 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"
- ♃ = Jupiter, or "jovian"

So when you see something like "Mars' radius is ≈ 0.53⊕", read it as "Mars' radius is ≈ 0.53 *terran*." Other examples:

- 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 ≈ 5.515 g/cm³; in **relative** terms it is 1.0⊕. 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.,

$$\rho☽ \approx \frac{3.344\ gm/cm^3}{5.514\ gm/cm^3} \approx 0.606⊕$$

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:

$$E = \frac{1}{d^2}$$

... 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.

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1. IAU RESOLUTION: DEFINITION OF A PLANET IN THE SOLAR SYSTEM. https://nssdc.gsfc.nasa.gov/planetary/text/pluto_iau_res_20060824.txt ↩
2. DeBenedictis, Tim. "Why Pluto Is a Planet, and Eris Is Too." Space.com, June 4, 2015. http://www.space.com/29571-why-pluto-is-a-planet-and-eris-is-too.html. ↩
3. Basri, Gibor; Brown, E. M. (May 2006). "Planetesimals to Brown Dwarfs: What is a Planet?". Annual Review of Earth and Planetary Sciences. 34: 193–216. arXiv:astro-ph/0608417. Bibcode:2006AREPS..34..193B. doi:10.1146/annurev.earth.34.031405.125058. S2CID 119338327. ↩

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^{24} kg
Radius (r)	6371 km
Density (ρ)	5.514 g/cm^3
Surface Gravity (g)	9.8 m/sec^2
Escape Velocity (v_e)*	11.186 km/sec

* Critical to retention of a sufficiently dense atmosphere.

In relative terms, each of these values defines a baseline of **1.000⊕** — where ⊕ 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 ⟨**0.500** ∧ **1.500**⟩⊕ 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:
>
> - ρ = 0.500⊕ = 2.757 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.
> - ρ = 1.500⊕ = 8.271 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:

> Planemo Equations of State
>
> | Mass (m) | Radius (r) | Density (ρ) | Gravity (g) | Escape Velocity (v_e) |
> |---|---|---|---|---|
> | $m = gr^2$ | $r = \frac{g}{\rho}$ | $\rho = \frac{m}{r^3}$ | $g = \frac{m}{r^2}$ | $v_e = \sqrt{gr}$ |
> | $m = \rho r^3$ | $r = \sqrt{\frac{m}{g}}$ | $\rho = \frac{g}{r}$ | $g = r\rho$ | $v_e = \sqrt{\frac{m}{r}}$ |
> | $m = \frac{g^3}{\rho^2}$ | $r = \sqrt[3]{\frac{m}{\rho}}$ | $\rho = \sqrt{\frac{g^3}{m}}$ | $g = \sqrt[3]{m\rho^2}$ | $v_e = \frac{g}{\sqrt{\rho}}$ |
> | $m = \frac{v_e^3}{\sqrt{\rho}}$ | $r = \frac{v_e}{\sqrt{\rho}}$ | $\rho = \left(\frac{v_e}{r}\right)^2$ | $g = v_e\sqrt{\rho}$ | $v_e = \sqrt[4]{mg}$ |
> | $m = \frac{v_e^4}{g}$ | $r = \frac{v_e^2}{g}$ | $\rho = \left(\frac{g}{v_e}\right)^2$ | $g = \frac{v_e^2}{r}$ | $v_e = r\sqrt{\rho}$ |
> | $m = rv_e^2$ | $r = \frac{m}{v_e^2}$ | $\rho = \left(\frac{v_e^3}{m}\right)^2$ | $g = \frac{v_e^4}{m}$ | $v_e = \sqrt[6]{m^2\rho}$ |

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).
2. For planemos, any given parameter is calculated as the relationship between **two other known** parameters.
3. *If any two parameters are 1.0⊕, 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 "throwing together a world", my recommendation is to always start with **density**, for the reasons outlined in [The Importance of Density].

A Basic Planemo

So let's start with a planemo of density ρ = 0.925⊕. 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 ⊕. Well, we can specify an exact value for another parameter; for instance, mass m = 1.100⊕. Now we can calculate any-and-all parameters that receive density and mass as inputs; gravity, for instance:

$$g = \sqrt[3]{\frac{m}{\rho^2}} = \sqrt[3]{\frac{1.1}{0.925^2}} = \sqrt[3]{\frac{1.1}{0.8556}} = \sqrt[3]{1.2856} = 1.0874\oplus$$

So far, so good; our density, mass, and gravity all fall within parameter limits:

- ρ = 0.925 ∈ ⟨0.5 ∧ 1.5⟩
- m = 1.1 ∈ ⟨0.5 ∧ 1.5⟩
- g = 1.0875 ∈ ⟨0.5 ∧ 1.5⟩

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:

$$r = \frac{g}{\rho} = \frac{1.0874}{0.925} = 1.1744\oplus$$

And this parameter is also within limits, so now we have:

- ρ = 0.925 ∈ ⟨0.5 ∧ 1.5⟩
- m = 1.1 ∈ ⟨0.5 ∧ 1.5⟩
- g = 1.0875 ∈ ⟨0.5 ∧ 1.5⟩
- r = 1.1744 ∈ ⟨0.5 ∧ 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 ← gravity and radius, and v_e ← mass and radius. Let's choose the latter:

$$v_e = \sqrt{\frac{m}{r}} = \sqrt{\frac{1.1}{1.1744}} = \sqrt{0.9358} = 0.9673\oplus$$

And now we have a full set of in-limit parameters:

- ρ = 0.925 ∈ ⟨0.5 ∧ 1.5⟩
- m = 1.1 ∈ ⟨0.5 ∧ 1.5⟩
- g = 1.0875 ∈ ⟨0.5 ∧ 1.5⟩

- $r = 1.1744 \in \langle 0.5 \wedge 1.5 \rangle$
- $v_e = 0.9673 \in \langle 0.5 \wedge 1.5 \rangle$

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: $\rho = 0.500\oplus$
- Gravity: $g = 1.500\oplus$

Plug these inputs into the equations of state, and out pop:

- $v_e = \dfrac{g}{\sqrt{\rho}} = \dfrac{1.500}{\sqrt{0.500}} = \dfrac{1.500}{0.707} = 2.121\oplus$
- $r = \dfrac{g}{\rho} = \dfrac{1.500}{0.500} = 3.000\oplus$
- $m = \dfrac{g^3}{\rho^2} = \dfrac{3.375}{0.250} = \mathit{13.500}\oplus$

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**:

- $v_e = \frac{g}{\sqrt{\rho}}$
- $r = \frac{g}{\rho}$
- $m = \frac{g^3}{\rho^2}$

  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 ¼ is the same thing as multiplying by 4.000, so:

  $$m = \frac{g^3}{\rho^2} = \frac{3.375}{0.250} = 3.375 \times 4.000 = \mathit{13.500}\oplus$$

  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 ∊ ⟨0.500 ∧ 1.500⟩ and ρ ∊ ⟨0.500 ∧ 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:

- g = 0.500; ρ = 0.500; m = 0.500
  - Mass at the minimum Geotic range
- g = 0.500; ρ = 1.500; m = 0.0556
  - Mass 0.444 below the Geotic range
- g = 1.500; ρ = 0.500; m = 13.500
  - Mass 12.0 above the Geotic range
- g = 1.500; ρ = 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⊕), *some value for gravity between ⟨0.500 ∧ 1.500⟩⊕* 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⊕, and we know that we want the density to be ρ = 0.5⊕, so we calculate the gravity necessary to produce these results by:

$$g = \sqrt[3]{m\rho^2} = \sqrt[3]{1.500 \times 0.500^2} = \sqrt[3]{1.500 \times 0.250} = \sqrt[3]{0.375} = 0.721\oplus$$

... and now we know that for a specified density of 0.5⊕, *no gravity above 0.721⊕* 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⊕ will produce a mass above the lower bound for Geotics... so our *permissible* range of gravity inputs is g ∈ ⟨0.500 ∧ 0.721⟩⊕.

> **Keppy**: So, we have to abandon our original requirement of g = 1.500⊕....

> **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 ρ ≤ 1.500⊕ will produce masses m > 1.500⊕, up to m = 13.500⊕ when ρ = 0.500⊕.

∴ to get any mass m < 1.500⊕, the input density must be ρ > 1.500⊕.

We can demonstrate this by calculating the minimum density necessary to produce m = 0.500⊕ combined with a gravity of g = 1.500⊕. We solve for density using these two mass and gravity inputs:

- m = 0.500⊕
- g = 1.500⊕

$$\rho = \sqrt{\frac{g^3}{m}} = \sqrt{\frac{1.500^3}{0.500}} = \sqrt{\frac{3.375}{0.500}} = \sqrt{6.750} = 2.5981\oplus$$

... which is 1.0981⊕ over our 0.500⊕ < ρ < 1.500⊕ limitation.

> **Keppy**: Can we stretch on the density?

Possibly; a density of basically ρ = 2.600⊕ 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 — Justifying The Geotic and Gaean Parameter Envelopes goes into more detail, if you're interested.

Sidebar — Close-focus on Parameter Precedence

1.01 — Planemo Classes

Planet Classes

> Telluric Planemos
>
> # Telluric
>
> **Telluric** := ⟨ m ∧ ρ ∧ g ∧ r ∧ v_e ⟩
> m := ⟨0.02 ∧ 10.00⟩⊕
> ρ := ⟨0.50 ∧ 7.00⟩⊕
> g := ⟨0.15 ∧ 8.00⟩⊕
> r := ⟨0.15 ∧ 3.00⟩⊕
> v_e := ⟨0.25 ∧ 3.00⟩⊕
>
> > 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 Planemos

Geotic

Geotic := ⟨ m ∧ ρ ∧ g ∧ r ∧ v_e ⟩
m := ⟨0.30 ∧ 3.35⟩⊕
ρ := ⟨0.85 ∧ 1.25⟩⊕
g := ⟨0.60 ∧ 1.65⟩⊕
r := ⟨0.60 ∧ 1.50⟩⊕
v_e := ⟨0.65 ∧ 1.50⟩⊕

$$\text{GEOTIC} := \left\{ (m,\rho) \in \mathbb{R}^2 \;\middle|\; \begin{array}{l} 0.30 \le m \le 3.35 \\ 0.85 \le \rho \le 1.25 \\ 0.60 \le g(m,\rho) \le 1.65 \\ 0.60 \le r(m,\rho) \le 1.50 \\ 0.65 \le v_e(m,\rho) \le 1.50 \end{array} \right\}$$

> *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.

Implication:

- Geotics may include:
  - **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.

Rheatic Planemos

Rheatic

Rheatic := ⟨ m ∧ ρ ∧ g ∧ r ∧ v_e ⟩
m := ⟨1.00 ∧ 3.00⟩⊕
ρ := ⟨0.85 ∧ 1.25⟩⊕
g := ⟨0.85 ∧ 1.70⟩⊕
r := ⟨0.90 ∧ 1.50⟩⊕
v_e := ⟨0.95 ∧ 1.50⟩⊕

$$\text{RHEATIC} := \left\{ (m, \rho) \in \mathbb{R}^2 \;\middle|\; \begin{array}{l} 1.00 \le m \le 3.00 \\ 0.85 \le \rho \le 1.25 \\ 0.85 \le g(m,\rho) \le 1.70 \\ 0.90 \le r(m,\rho) \le 1.50 \\ 0.95 \le v_e(m,\rho) \le 1.50 \end{array} \right\}$$

> *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 Planemos

Xenotic

Xenotic := ⟨ m ∧ ρ ∧ g ∧ r ∧ v_e ⟩

m := ⟨0.0001 ∧ 4131⟩⊕

ρ := ⟨0.01 ∧ 7.00⟩⊕

g := ⟨0.02 ∧ 60.00⟩⊕

r := ⟨0.02 ∧ 11.00⟩⊕

v_e := ⟨0.02 ∧ 25.00⟩⊕

$$\text{XENOTIC} := \left\{ (m,\rho) \in \mathbb{R}^2 \;\middle|\; \begin{array}{l} 0.0001 \le m \le 4131 \\ 0.01 \le \rho \le 7.00 \\ 0.002 \le g(m,\rho) \le 60.00 \\ 0.02 \le r(m,\rho) \le 11.00 \\ 0.02 \le v_e(m,\rho) \le 25.00 \end{array} \right\}$$

> *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 — might arise.