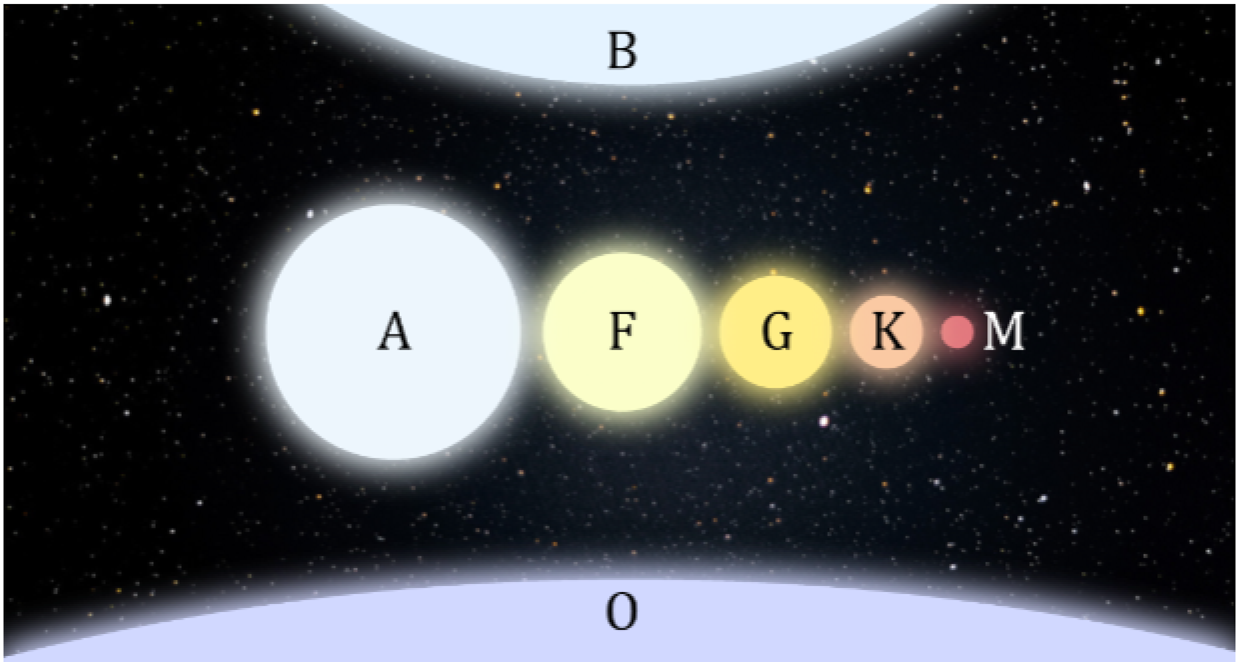
M002 - Stars — 00 Compendium

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 Sidebar: The Spectral System and the Women Who Built It.

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 Sidebar Module: _Mind the Gap — The Shortcomings of the Traditional Spectral Scale_.

Spectral Class Table

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

Spectral Class	Low Temp. (K)	High Temp. (K)
O	25000	55000
B	10000	25000
A	7500	10000

Spectral Class	Low Temp. (K)	High Temp. (K)
F	6000	7500
G	5000	6000
K	3500	5000
M	2400	3500
Brown ↓ Dwarfs ↓		
L	1300	2400
T	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_{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).

$$Ƨ = \frac{\kappa - K}{þ}$$

$$\kappa = Ƨþ + K$$

$$K = \kappa - Ƨþ$$

$$þ = \frac{\kappa - K}{Ƨ}$$

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
- Ƨ = the spectral *type* number

The Thermal Interval Constant (þ)

Where does þ come from?
For a given spectral class þ can be calculated by:

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

Here is the above table with these constants added:

Spectral Class	Low Temp. (Kelvin)	High Temp. (Kelvin)	Thermal Interval Constant (þ)
O	25000	55000	3000
B	10000	25000	1500
A	7500	10000	250
F	6000	7500	150
G	5000	6000	100
K	3500	5000	150
M	2400	3500	110
L	1300	2400	110
T	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 (þ) for spectral class G is þ = 100

- What is the Sun's spectral type (Ƨ)
  Running the numbers:

$$\begin{aligned}
&\text{Ƨ} = \frac{\kappa - K}{\text{þ}} \\
&\text{Ƨ} = \frac{6000 - 5800}{100} \\
&\text{Ƨ} = \frac{200}{100} \\
&\text{Ƨ} = 2 \checkmark
\end{aligned}$$

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

$$\begin{aligned}
&K = \kappa - \text{Ƨþ} \\
&K = 6000 - (2)(100) \\
&K = 6000 - 200 \\
&K = 5800 \checkmark
\end{aligned}$$

  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 ∈ ⟨6000 ∧ 7500⟩.
- The thermal interval constant for spectral class F is þ = 150.
  Working through the equation:

$$\begin{aligned}
&K = \kappa - \text{Ƨþ} \\
&K = 7500 - (3.65)(150) \\
&K = 7500 - 547.5 \\
&K = 6952.5 \checkmark
\end{aligned}$$

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*⊙.

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⊙. 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 þ = 100

The spectral type is:

$$\text{ꝛ} = \frac{\kappa - K}{\text{þ}}$$

$$\text{ꝛ} = \frac{6000 - 5080.8}{100}$$

$$\text{ꝛ} = \frac{919.2}{100}$$

$$\text{ꝛ} = 9.192 \checkmark$$

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

Parameter Ranges By Spectral Class

	SC →	O	B	A	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
	TIC[1] (*þ*)	3000	1500	250	150	100	150	110

	SC →	O	B	A	F	G	K	M
	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

[1] 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 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** (ρ) 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 Sidebar — What Is The Main Sequence).

> **Keppy**: And a **blackbod**y 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)
$T = \sqrt[1.98]{M}$	$M = \sqrt[0.9]{R}$	$R = M^{0.9}$	$Q = M^{-2.5}$
$T = \sqrt[1.8]{R}$	$M = T^{1.98}$	$R = T^{1.8}$	$Q \approx \sqrt[-0.36]{R}$
$T = Q^{-0.2}$	$M = Q^{-0.4}$	$R = Q^{-0.36}$	$Q = T^{-5}$

> > **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:

- $4\pi R^2$ = the surface area of the body
- T = is the temperature of the body in Kelvin
- σ = the Stefan-Boltzmann constant
  - $\sigma = 5.670374419 \times 10^{-8} W m^{-2} K^{-4}$
    - **Watts** per square meter per Kelvin to the fourth power 1 K^4
    - 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^4**.

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_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 $T = \frac{K_s}{K_{Sun}}$, this equation becomes:

$$L = R^2 T^4, \qquad \text{with derivations of}$$

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

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⊙ for 5800 K, R = 1⊙ for the solar radius, etc.

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

Primary dependency chain: T/K → R → L → M → Q

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

Starting with Mass (*M*)

Primary dependency chain: M → T/K → R → L → Q

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

Starting with Radius (*R*)

Primary dependency chain: R → T → K → L → M → Q

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

Starting With Luminosity (*L*)

Primary dependency chain: L → T → K → R → M → Q

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

Starting with Lifetime (*Q*)

As soon as you assume you'd never want to do this, you'll find a case for doing it.

As soon as you assume you'd never want to do this, you'll find a case for doing it.
Primary dependency chain: Q → T → K → R → L → 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 1.496×10^8 km — is defined as one **astronomical unit (AU)**. Due to Earth's slightly elliptical orbit, this distance varies by approximately ±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:

$$\begin{gathered} N = 0.7071\ AU \\ \text{Inner Edge} = 0.950N = (0.950)(0.7071) = 0.6717\ AU \\ \text{Outer Edge} = 1.385N = (1.385)(0.7071) = 0.9793\ AU \end{gathered}$$

> **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 ∧ 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 (ғ)

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 $4.850\ AU$ ғ 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 — 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"

* Assuming they are otherwise Earth-like in size and composition.

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_0	0.500N
H_1	0.750N
H_2	0.950N
H_3	1.385N
H_4	1.770N
H_5	4.850N

Adding these to our earlier table:

Thermozone	Zone Limits	Orbital Range	Ontozones	Notation
Igniozone	← H_0	← 0.500N	Inner Xenotic Zone	Z_{IX}
Calorozone	⟨H_0 ∧ H_1⟩	⟨0.500 ∧ 0.750⟩N	Inner Parahabitable Zone	Z_{IP}
Heliozone	⟨H_1 ∧ H_2⟩	⟨0.750 ∧ 0.950⟩N	Inner Habitable Zone	Z_{IH}
Solarazone	⟨H_2 ∧ H_3⟩	⟨0.950 ∧ 1.385⟩N	Hospitable Zone	Z_H
Hiberozone	⟨H_3 ∧ H_4⟩	⟨1.385 ∧ 1.770⟩N	Outer Habitable Zone	Z_{OH}
Brumazone	⟨H_4 ∧ H_5⟩	⟨1.770 ∧ 4.850⟩N	Outer Parahabitable Zone	Z_{OP}
Cryozone	H_5 →	4.850N →	Outer Xenotic Zone	Z_{OX}

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:

$$365.256363004 \quad \text{Ephemeris Days}$$
$$or$$
$$365^d\ 6^h\ 9^m\ 9.763545^s$$

> 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 Sidebar — Units and Measures of Time 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:

$$\begin{aligned} P &= \sqrt{\frac{a^3}{M+m}} \\ a &= \sqrt[3]{P^2(M+m)} \\ M+m &= \frac{a^3}{P^2} \qquad \text{Believe it or not, this has its uses} \end{aligned}$$

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:

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

Calculating with **only** the Sun's mass:

$$P = \sqrt{\frac{a^3}{M}} = \sqrt{\frac{1^3}{1}} = \sqrt{\frac{1}{1}} = \sqrt{1} = 1 \text{ years}$$

Calculating with **both** masses:

$$\begin{aligned} P &= \sqrt{\frac{a^3}{M+m}} \\ &= \sqrt{\frac{1^3}{1+0.000003003}} \\ &= \sqrt{\frac{1}{1.000003003}} \\ &= \sqrt{0.999997} \\ P &= 0.9999985 \text{ years} \end{aligned}$$

… a difference of about 47.384 *seconds*.

> 🔍 **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:
>
> $$\begin{aligned} A &= \sqrt[3]{M+m} && \text{When taking into account both masses} \\ A &= \sqrt[3]{M} && \text{When using only the central mass} \end{aligned}$$

> M002 - Stars — 06 Relating the Nucleal and Perannual Years
>
> We have explored both [The Nucleal Orbit] and [The Perannual Orbit]. 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}$$
>
>   This means that:
> - The perannual orbit can be *approximated* directly from the luminosity by:
>
> $$A \approx \sqrt[3]{\sqrt[3]{L}} \approx \sqrt[6]{L}$$

> - The nucleal orbit can be *approximated* directly from the mass by:
>
> $$N \approx \sqrt{M^3}$$
>
> And, by extension either can be *approximated* from the other by:
>
> $$A \approx \sqrt[6]{N^2} \approx \sqrt[3]{N}$$
> $$N \approx A^3$$
>
> **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)
$T = \sqrt[1.98]{M}$	$M = \sqrt[0.9]{R}$	$R = M^{0.9}$	$Q = M^{-2.5}$
$T = \sqrt[1.8]{R}$	$M = T^{1.98}$	$R = T^{1.8}$	$Q \approx \sqrt[-0.36]{R}$
$T = Q^{-0.2}$	$M = Q^{-0.4}$	$R = Q^{-0.36}$	$Q = T^{-5}$

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)
$T = \sqrt{M}$	$M = \sqrt[0.9]{R}$	$R = M^{0.9}$	$Q = M^{-2.5}$	$L = M^{3.8}$
$T = \sqrt[1.8]{R}$	$M = T^{2}$	$R = T^{1.8}$	$Q \approx \sqrt[-0.36]{R}$	$L \approx R^{4.\bar{2}}$
$T = Q^{-0.2}$	$M = Q^{-0.4}$	$R = Q^{-0.36}$	$Q = T^{-5}$	$L = T^{7.6}$
$T = \sqrt[7.6]{L}$	$M = \sqrt[3.8]{L}$	$R \approx \sqrt[4.\bar{2}]{L}$	$Q = L^{-1.52}$	$L = \sqrt[-1.52]{Q}$

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

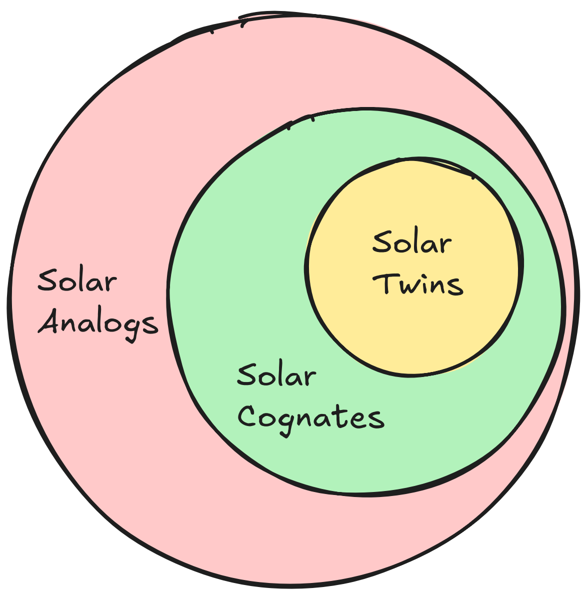
For thesiastic purposes, our criteria need to be more related to the *habitability* of orbiting planemos than directly to physical similarity between stars. Therefore, WBN defines the following:

Solar Analogs:

- Stars whose *perannual orbits* fall within ⟨0.500, 4.850⟩ AU, spanning from the Inner Parahabitable Zone to the Outer Parahabitable Zone (H_0 – H_5).
  Solar Cognates:
- Stars whose *perannual orbits* fall within ⟨0.750, 1.770⟩ AU, spanning from the Inner Habitable Zone to the Outer Habitable Zone (H_1 – H_4).
  Solar Twins:
- Stars whose *perannual orbits* fall within ⟨0.950, 1.385⟩ 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 based on Perannual Orbit Position



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:

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

… and solve for L:

$$\begin{aligned} \sqrt[11.4]{L} &= 0.500\sqrt{L} \\ 0.500 &= \frac{\sqrt[11.4]{L}}{\sqrt{L}} \\ &= L^{\frac{1}{11.4} - \frac{1}{2}} \\ &= L^{\frac{2}{22.8} - \frac{11.4}{22.8}} = L^{-\frac{9.4}{22.8}} \\ 0.500 &= L^{-0.4123} \\ L &= \sqrt[-0.4123]{0.500} \\ &= 5.372 \checkmark \end{aligned}$$

Converting luminosity to temperature:

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

In 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:

$$\text{ƨ} = \frac{\kappa - K}{p}$$

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
- Ƨ = the spectral *type* number

Taken from the table:

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

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

- κ = 7500
- þ = 150

$$Ƨ = \frac{\kappa - K}{þ} = \frac{7500 - 7235.97}{150} = \frac{264.03}{150} = 1.76$$

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

Generalizing The Equation

By generalizing the inner habitability limit factor λ\lambdaλ, we can calculate the spectral type for **any** perannual orbit distance:

$$\begin{aligned}
\sqrt[11.4]{L} &= \lambda\sqrt{L} \\
\lambda &= \frac{\sqrt[11.4]{L}}{\sqrt{L}} \\
&= L^{\frac{1}{11.4}-\frac{1}{2}} \\
&= L^{\frac{2}{22.8}-\frac{11.4}{22.8}} = L^{-\frac{9.4}{22.8}} \\
\lambda &= L^{-0.4123} \\
\therefore L &= \sqrt[-0.4123]{\lambda}\ ✓
\end{aligned}$$

A Final Determination

Substituting all of the H_x values in for λ:

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 calculation is:

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

… 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