Foundations of Worldbuilding:

Getting the Astronomy Right

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Outline

- **Introduction**
- **Frequency of Earthlike Worlds**
- **The Exoplanetary Revolution**

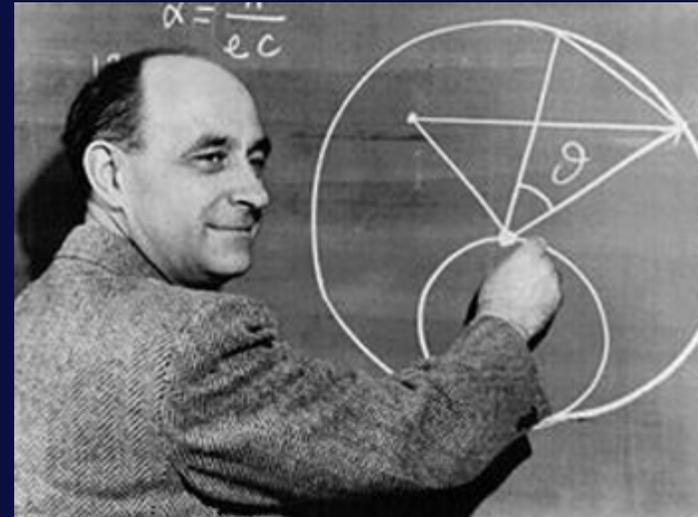# Introduction

Frequency of Earthlike Worlds

A Question

> **How many Earthlike worlds are there in any given volume of space in the real galaxy?**

Some Answers

- The honest answer: "We don't know (yet)."

- Also: "Define *Earthlike*."

- We can, however, make a *Fermi estimate!*

Defining "Earthlike"

Earthlike World: A terrestrial or "rocky" body which supports a significant amount of liquid water on its surface long enough that life can evolve, produce significant free oxygen in the atmosphere, and give rise to a complex ecology.

In short, "could humans have at least a chance to visit, walk around without lots of life-support equipment, and talk to any smart critters that live there?"

How Many Stars Are There?

> **In our neighborhood of the galaxy, there is 1 star system (possibly including more than one star) every 12-13 cubic parsecs.**

- Source: the *Gaia* mission

- 336 star systems within 10 parsecs of Sol (gives us 1 star system per ~12.5 pc^3)

- Does not count possible open clusters and stellar associations (but we don't need to)

C. Reyle *et al*, "The 10 parsec sample in the Gaia era: first update" (arXiv:2302.02810v2)
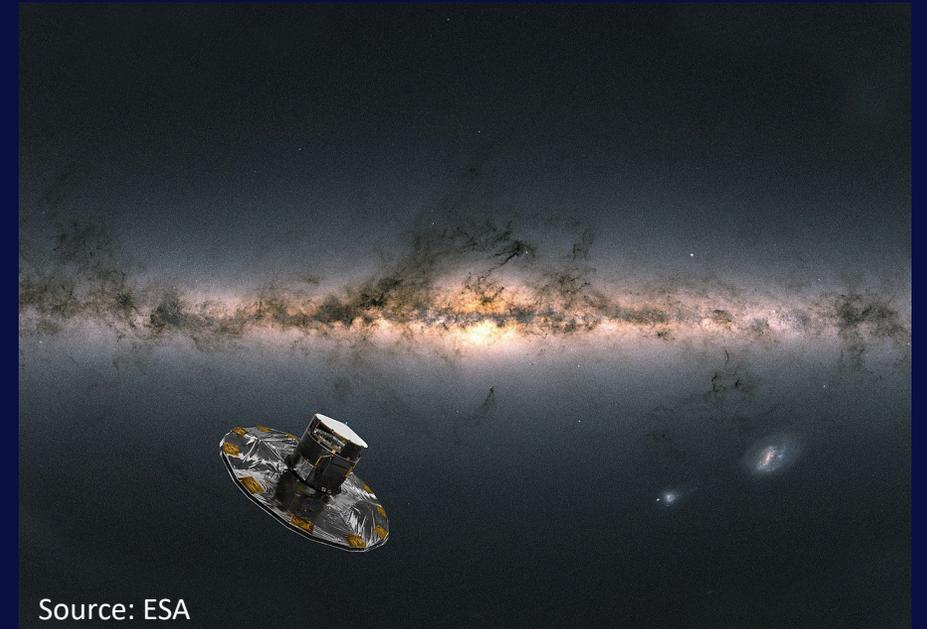
Source: ESA

How Many Stars Have Planets?

> **"All of them" appears to be a reasonable assumption.**

- Ten-parsec sample (as of 2023) shows ~28 star systems with planets (~8%) – more are being identified all the time

- Models for stellar formation suggest *every* star is likely to develop planets, although not every star will necessarily *keep* the planets that form

Major exception: stars in close binary pairs

Habitable Zones

- The *habitable zone* around a star is the range of orbital radii where a planet can support liquid-water oceans

- How many planets is a star likely to have in the habitable zone at any given time?

Source: NASA
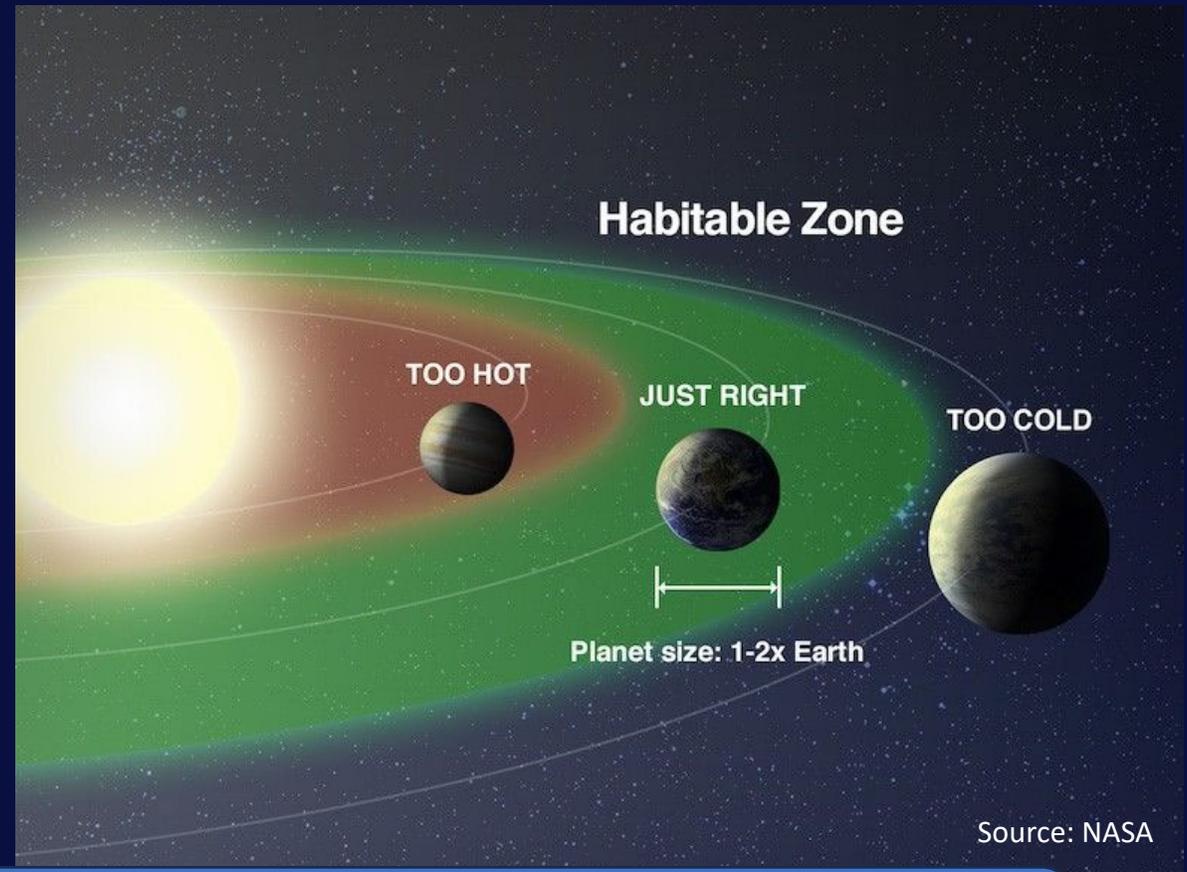
**"About 1 per star" appears to be a reasonable assumption.**

Habitable Zones

> ### *How long* will a given planet be located in its star's habitable zone?

- Stars evolve, and their luminosity increases over time!
- This implies the habitable zone *moves outward*

- Planets need *time* to develop oxygen-rich atmospheres and complex ecologies
- Earth itself has only been "Earthlike" for about 540 million years out of 4.6 billion
- **A planet needs to *stay* in the habitable zone for several billion years!**

Habitable Zones

- More massive stars become more luminous more quickly (and leave the stable *main sequence* more quickly)

- As a rough estimate: a star needs to have a main sequence lifespan of at least 6 billion years, so a planet can spend at least 4 billion years in the habitable zone

- **This implies the star can have no more than ~1.2 solar masses (spectral type F8V or later)**

- Also, the star needs to **currently be at least 4 billion years old** (which is why we don't worry about clusters)
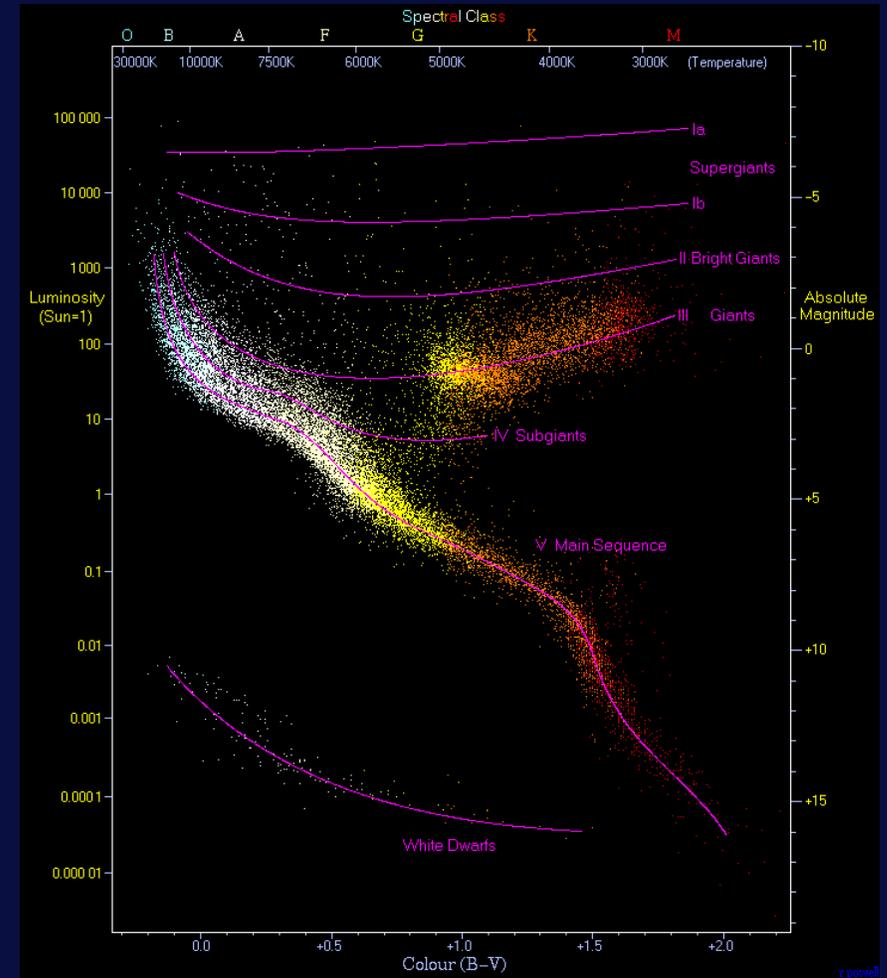
Source: Wikipedia

What About Low-Mass Stars?

- Low-mass stars (late K-type and M-type red dwarfs) are likely to have planets and have *very long* stable lifespans

- *Tide-locking* is guaranteed for otherwise habitable planets of such stars – but this is probably not a serious problem!

- A more serious concern: what about *photosynthesis* when most of your sunlight is in the red or infrared bands?
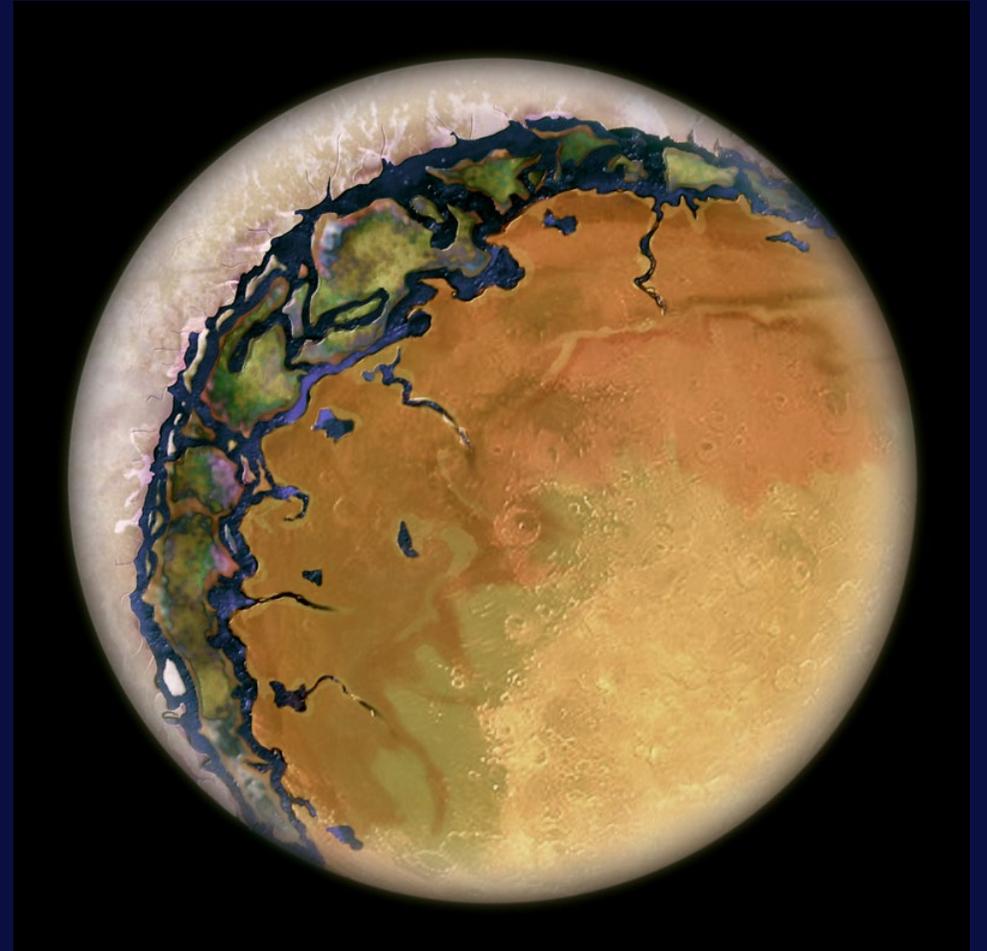
Source: Beau.TheConsortium (Rare Earth Wiki)

Photosynthesis and Low-Mass Stars

- Photosynthesis in the red and near-infrared bands is possible, *but . . .*
  - It's very inefficient (low-energy quanta)
  - Infrared light doesn't penetrate shallow water well

- Planets of low-mass stars may take a *very long time* to develop oxygen-rich atmospheres (if they ever do)

- Evidence is lacking (James Webb may eventually help)

- For now, best guess is that **a star needs to be spectral type K8V or earlier (~0.66 solar masses or more)** to support high-energy photosynthesis

Summary of Constraints

To have a good chance of an Earthlike world, a star must . . .
- Be either a singleton, or a member of a binary pair with wide separation
- Be at least 4 billion years old
- Have mass between about 0.66 to 1.2 solar masses (spectral class K8V to F8V)

So, how many star systems within 10 parsecs have at least one?

The List

Alpha Centauri A	Sigma Draconis	96 G. Piscium	Zeta Tucanae
Alpha Centauri B	Gliese 570 A	107 Piscium	41 G. Arae A
61 Cygni A	Eta Cassiopeiae A	Mu Cassiopeiae A	HD 192310
61 Cygni B	Eta Cassiopeiae B	p Eridani A	HR 1614
Tau Ceti	HR 7703	p Eridani B	Groombridge 1830
Groombridge 1618	82 G. Eridani	HD 217357	Gamma Pavonis
40 Eridani A	Delta Pavonis	Mu Herculis Aa	HD 102365 A
70 Ophiuchi A	HR 8832	Beta Canum Venaticorum	HR 4458 A
70 Ophiuchi B	268 G. Ceti A	61 Virginis	HD 151288

36 stars in 31 star systems within 10 parsecs

Some of these are borderline cases (there are some that *almost* made the list too)

Some Conclusions

- Our Fermi estimate – based on the ten-parsec *Gaia* sample – says about 9% of star systems in a "typical" neighborhood have a good chance of at least one Earthlike world

- About one "interesting" star system for every 135 pc^3

- Typical distance between "interesting" star systems: about 6 pc

- Several of these star systems are already known to have exoplanets!

- Detecting Earth-sized worlds is not *quite* doable yet in most cases – and we have yet to detect *any* truly Earthlike worlds

Implications for World-Building

- Most star systems will be quiet – there may be a *lot* of almost-Earthlike worlds out there with nothing more complex than bacteria living on them!

- Gives us an idea of *scale* and *speed* – how fast do you want your starship to be able to travel about 6 parsecs?

- *Intelligent life* is likely very rare in the universe – it has existed on Earth for only about 0.2% of its time as an Earthlike world (partial solution to Fermi Paradox)

- ET civilizations aren't going to come to Earth looking for anything but *us* – they'll have plentiful sources for any merely physical commodity much closer to home
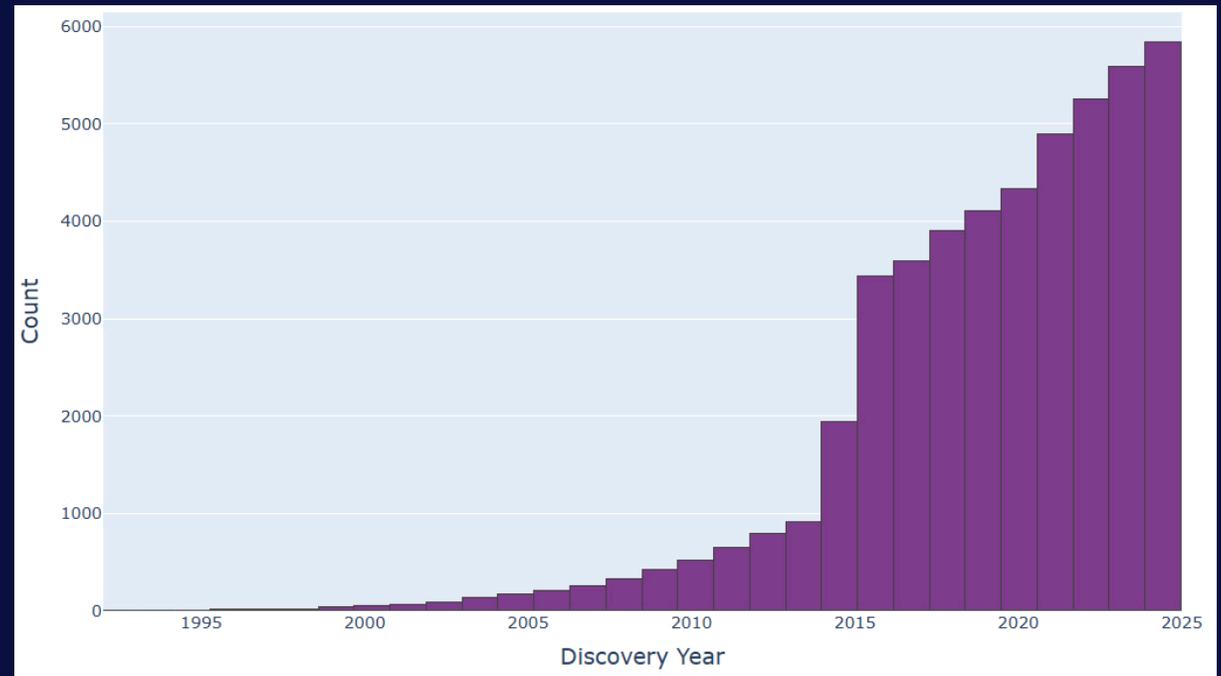
The Exoplanetary Revolution

Exoplanets Everywhere!

- First exoplanet detected (1992) – millisecond pulsar PSR B1257+12

- First exoplanet around a main-sequence star (1995) – 51 Pegasi

- Kepler Space Telescope (2009-2018)

- **September 2025: 5,989 *confirmed***
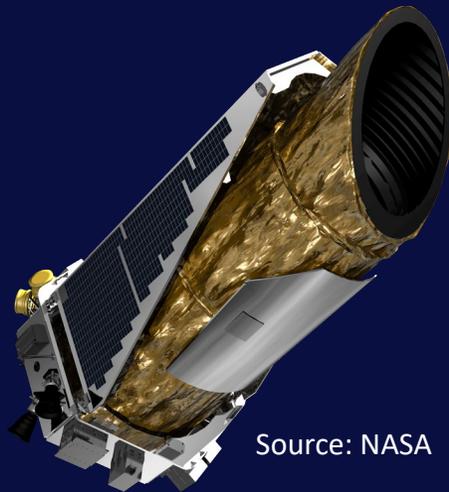
Source: NASA

Data Source: NASA Exoplanet Archive

Detection Methods: The Transit Method

- Most common method (Kepler and other telescopes)

- If an exoplanet's orbit is "edge on" to Earth, we see it pass in front of its primary star – reduction in star's luminosity gives us the exoplanet's *radius*

- No way to estimate the exoplanet's *mass* so we must guess at its composition

- Can (*rarely*) give us insight into planetary atmospheres
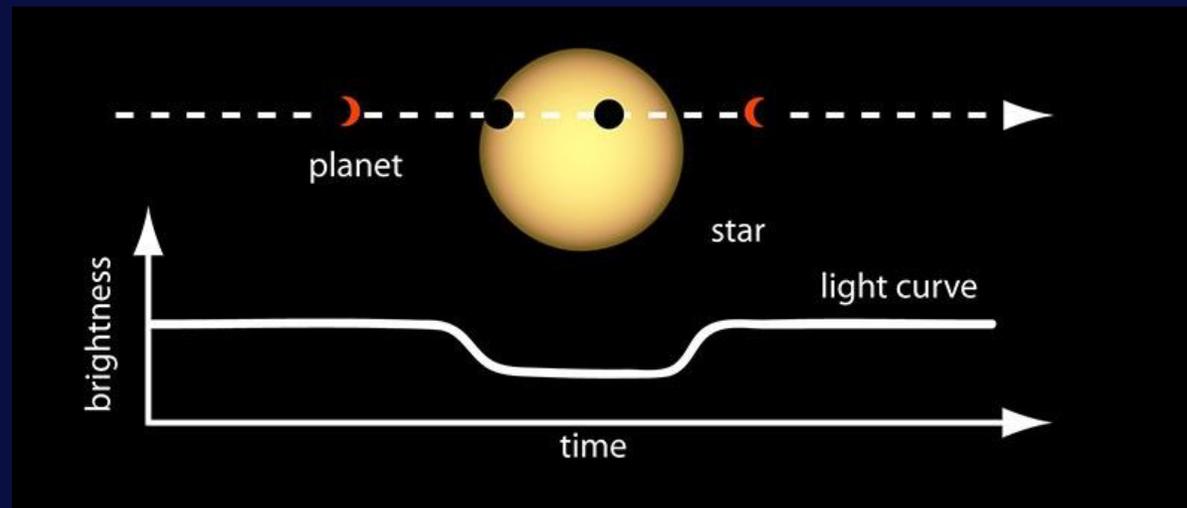
Source: NASA

## Detection Methods: The Radial-Velocity Method

- If we see evidence that a star's *radial velocity* varies slightly on a regular basis, we can infer the presence of an exoplanet

- We can estimate a *minimum mass* for the exoplanet based on the degree to which the star's radial velocity changes

- Actual mass depends on the inclination of the exoplanet's orbit to our line of sight

- No way to estimate *radius* and so density and composition

HOST STAR
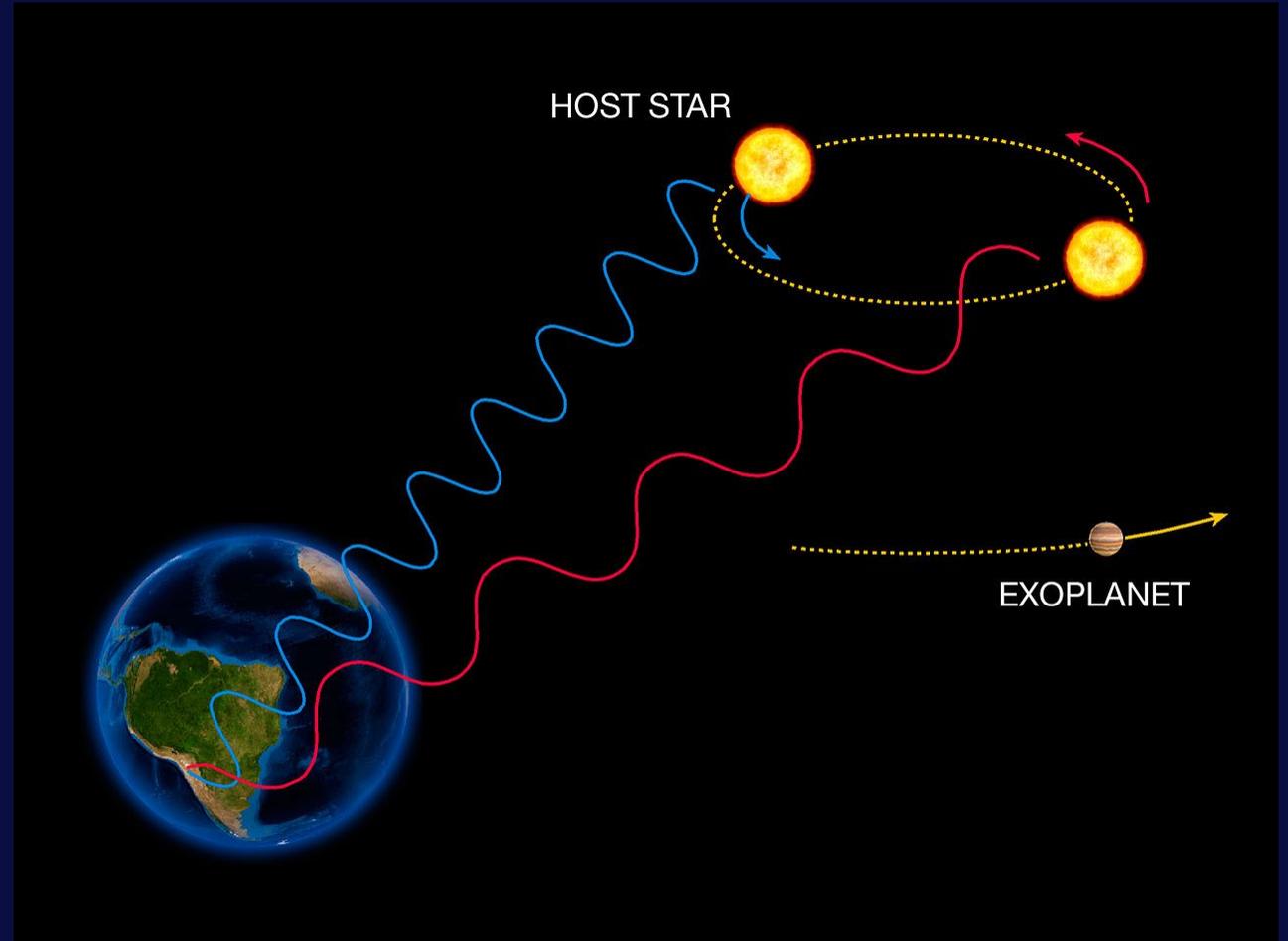
EXOPLANET

Source: ESO

Detection Methods: Direct Imaging

- In the case of some *nearby* stars, it's possible to *image* an exoplanet directly

- Need to block out the light of the primary star ("fireflies next to spotlights")

- Works best with *infrared* imaging (e.g., the James Webb telescope)

- Works best for *very young* planetary systems (hot planets still in process of formation)

- Can't directly measure *either* the mass or the radius of the exoplanets (but astrometry can help here)
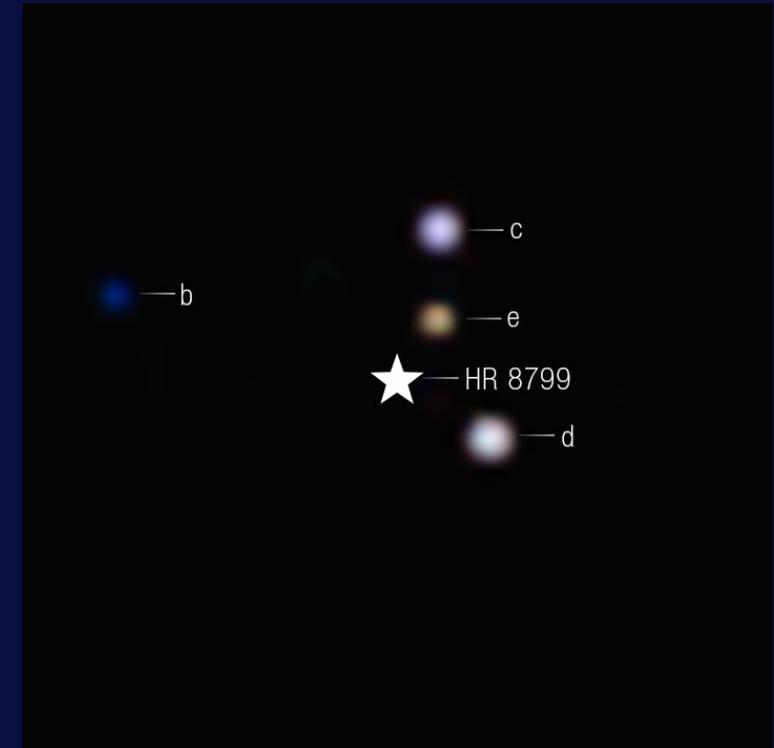
Source: NASA

Some Results

So, what have we learned in the past 30+ years?

- Planetary systems are as "tightly packed" as possible while staying long-term stable – one way this happens is via *orbital resonances*

- Planets – especially massive "gas giants" – *migrate* during formation

- Formation process for rocky "terrestrial" worlds is often extremely violent
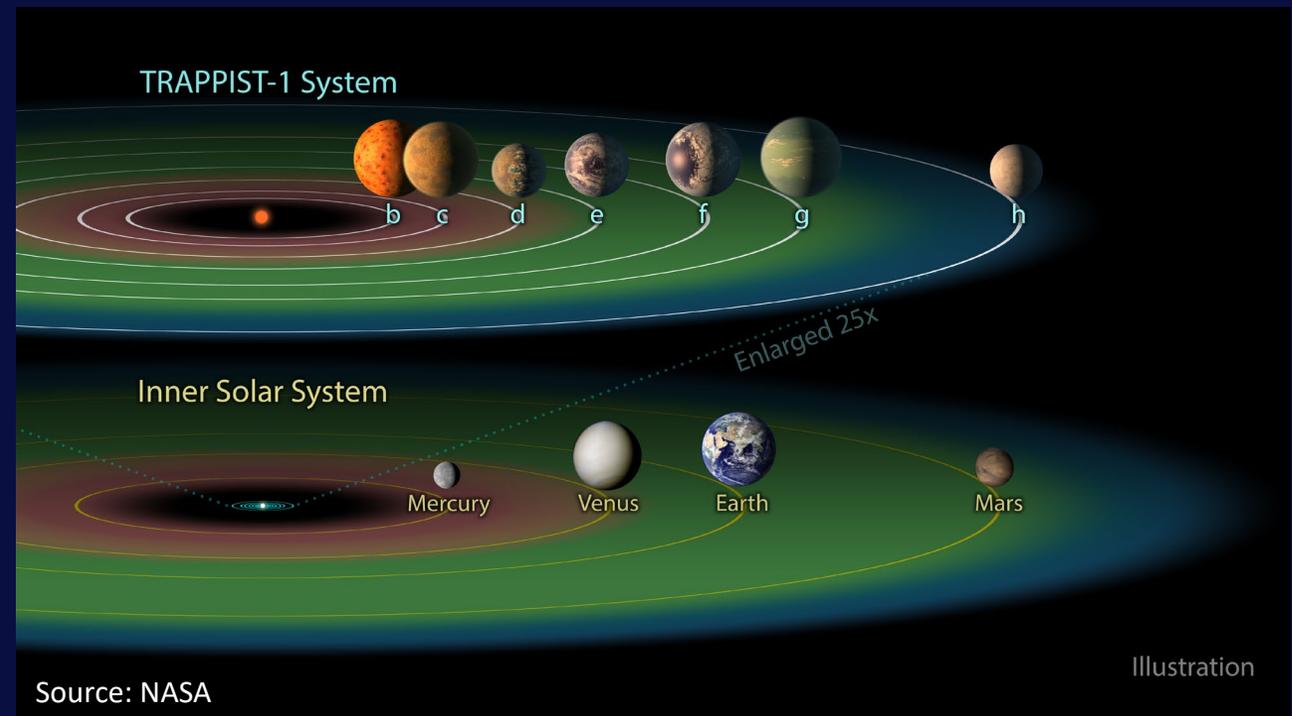
Orbital Resonances

Orbital Resonance: situation in which two (or more) orbiting bodies exert regular, periodic gravitational influence on each other, usually because their orbital periods are in a small-integer ratio

- Resonance can lead to *instability* (pushing an object out of its current orbit) but can also lead to *stability* (orbits are mutually correcting)

- **Example:** Inner Galilean satellites of Jupiter are in a very stable 4:2:1 resonance (Laplace resonance)

Example: TRAPPIST-1 Planetary System

- Ultra-cool red dwarf star, discovered in 1999

- Planetary system discovered in 2016 - seven planets, *extremely* tightly packed

- Orbits appear to be long-term stable due to a "stack" of orbital resonances:
    - 8:5
    - 5:3
    - 3:2
    - 3:2
    - 4:3
    - 3:2

TRAPPIST-1 System

b c d e f g h

Enlarged 25x

Inner Solar System

Mercury Venus Earth Mars

Source: NASA

Illustration

Resonances and World-building

- When designing a fictional planetary system, consider using orbital resonances to help make the arrangement stable . . .

- . . . but avoid *unstable* resonances (2:1, 3:1, 4:1, and so on) – ratios in which the integers are mutually prime are preferable . . .

- . . . but a *Laplace resonance* is a "stack" of at least two 2:1 ratios, and can be very stable

- Especially useful: tightly packed planetary systems for low-mass (red dwarf) stars

Imagine living in a planetary system arranged like this!

Planetary Migration

- **The old assumption:** Planets stay where they formed, "gas giants" in the outer planetary system, rocky "terrestrial" worlds closer to the star.

- Discovery of "hot Jupiters" posed a serious puzzle!

- **The new assumption:** Planets, especially "gas giants," can and often do *migrate* from their original positions in the process of formation.

Mechanisms for Migration

- During formation, a massive planet interacts with the gas of the *protoplanetary disk*

- This can exert *torque* and cause the planet to spiral inward or (sometimes) outward

- Three different types of migration, with different requirements

- Migration can occur at very different rates, depending on planetary mass and structure and viscosity of the gas disk

- Orbital resonances can modify (or be created by) the migration process
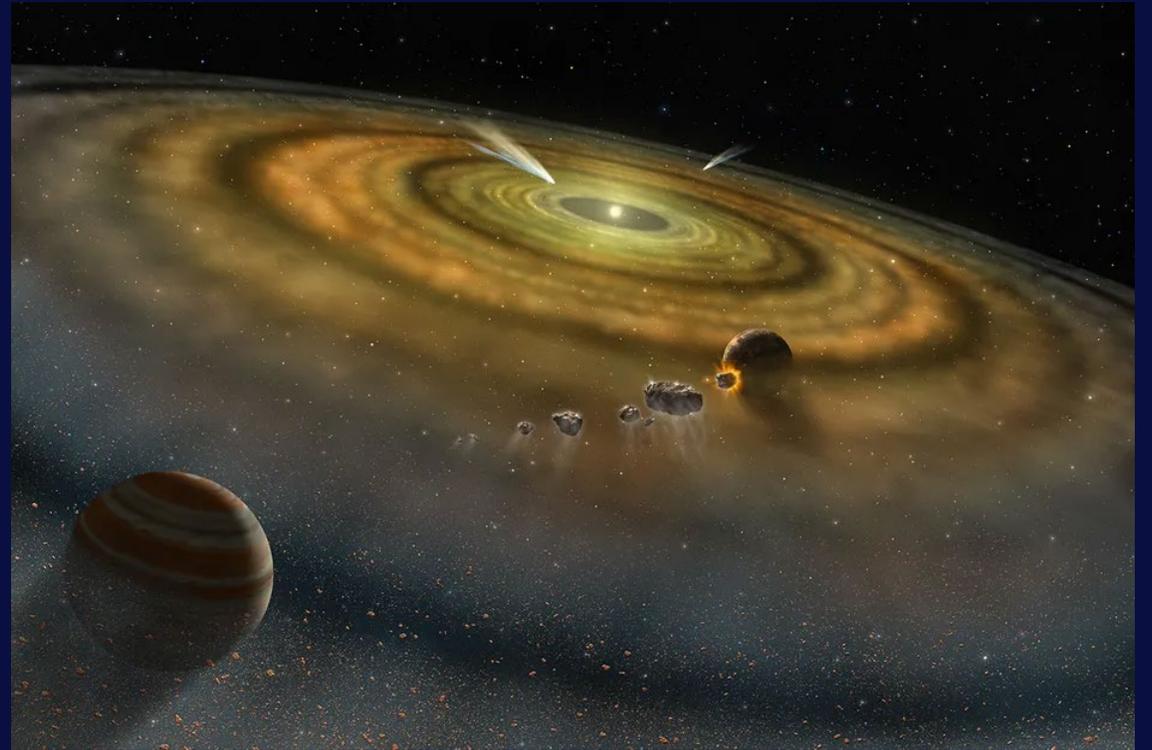

Source: NASA

Very fast inward migration -> "hot Jupiter"

Case Study: The "Grand Tack" Hypothesis

- Jupiter originally forms at 3.5 AU, begins inward migration

- Saturn forms and begins faster inward migration, eventually falls into a 3:2 resonance with Jupiter – this *halts* inward migration for both – Jupiter at 1.5-2.0 AU at this point

- Jupiter and Saturn clear the gas disk in their neighborhood and begin *outward* migration – Jupiter ends at its current position (5.2 AU)

- Possibly helps to explain:
  - Absence of "super-Earths" in our planetary system
  - Small size of Mars
  - Presence of the Asteroid Belt, including icy asteroids
  - Scattering of ice-bearing planetesimals into the inner system – presence of water on Earth
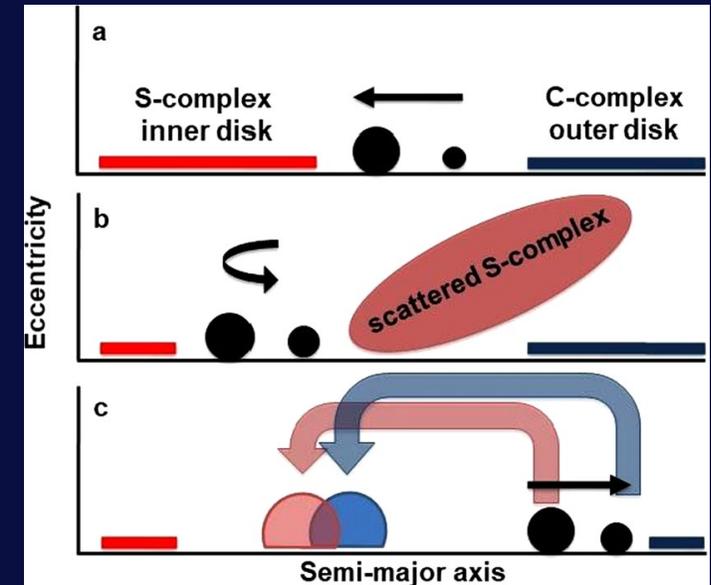
Source: ResearchGate

Planetary Migration and World-Building

Consider multiple possible end-states for the primary gas-giant planet:

- No migration: "super-Earth" terrestrial worlds, possibly water-deprived
- Moderate migration: terrestrial worlds have less material to build with and end up smaller
- Aggressive migration: "hot Jupiter," terrestrial worlds may form in the gas giant's wake (rocky planetesimals scattered outward)
- "Grand Tack" variant pushes primary gas giant back outward, delivers extra water to the inner system (better water worlds)

Variations in gas-giant migration may provide most of the variety in different planetary-system architectures

Oligarchic Formation of Terrestrial Worlds

- Terrestrial ("rocky") planets form last (most of the process *after* the dispersal of the gas disk)

- Process involves formation of *oligarchs* – protoplanets of about 0.01 to 0.1 Earth masses, which have collected most of the earlier planetesimals

- In late stages of the process, there may be *dozens* of oligarchs, many of them with inclined or eccentric orbits which cross one another

Final formation of terrestrial planets involves *oligarchic collisions* which can be extremely violent!
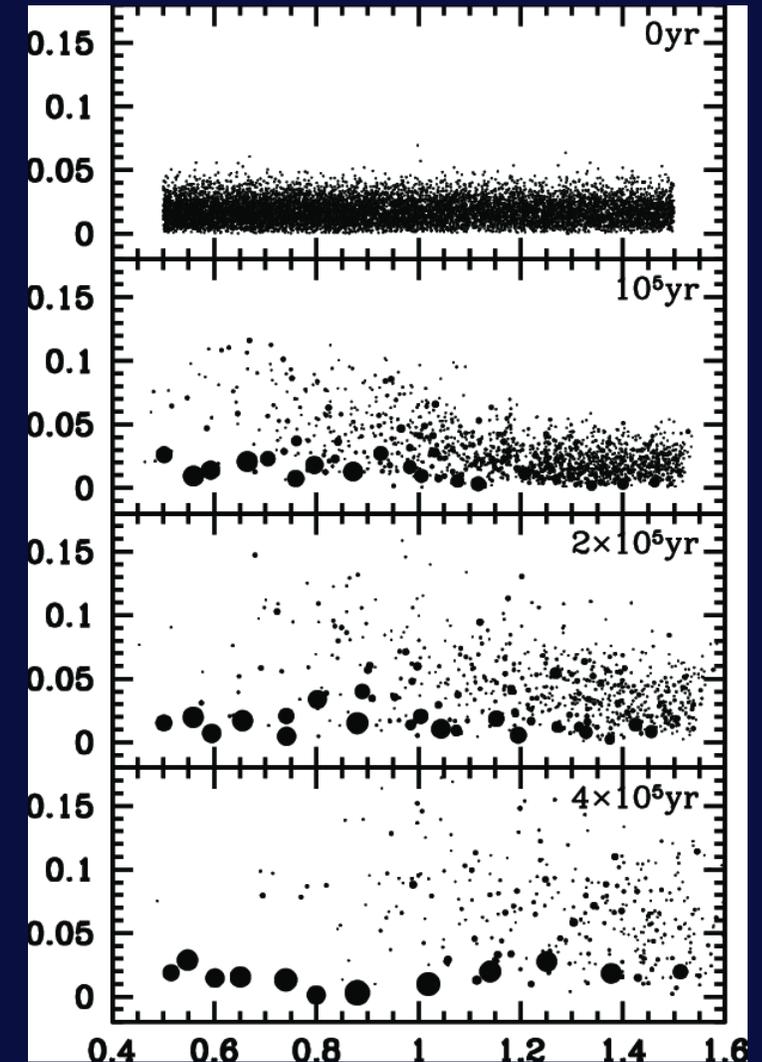
Source: ResearchGate

Examples: Mercury and Mars

- Mercury and Mars are both much smaller than Venus and Earth (about 0.1 Earth mass each)

- Each planet shows signs of extremely violent collisions late in formation era

- Mercury's density is very high, as if it's the nickel-iron core of a planet most of whose lighter layers have been blasted away

- The *entire northern hemisphere* of Mars may be the Solar System's biggest impact basin

These are effectively *surviving oligarchs*

Sources: NASA

Example: Earth

- Earth was likely formed by the collisional accretion of 8-12 oligarchs

- Final collision in the formation era: the "Big Whack" delivered by a Mars-sized (or larger) oligarch, tentatively named *Theia*

- Theia may have originally formed near one of Earth's Lagrange points, eventually perturbed away by interactions with Venus or Jupiter

- Material thrown off Earth in the collision gave rise to Earth's Moon

- Remains of Theia may have been identified in Earth's core

Source: NASA

Example: Earth and Moon

- Moon formed *very close* to Earth, but was driven outward very quickly by tidal interactions

- Models predict that more than one proto-Moon *may* have formed, but all but one was lost (ejected or collided) very quickly

Earthlike worlds elsewhere may have large moons via a similar process – but most likely only one apiece, and at wide separation


Source: Dan Durden/Southwest Research Institute

Oligarchs and World-Building

- Most planetary systems are likely to have one or two *surviving oligarchs* (roughly Mars-sized planets with interesting geological history)

- Terrestrial or "rocky" worlds are likely to show signs of a very violent early history (enormous impact basins, loss of light silicate materials, presence of a large natural satellite)

- On the other hand, terrestrial worlds are *unlikely* to have *more than one* large natural satellite!

Large satellites tend to stabilize a terrestrial world's rotation axis – what happens if there isn't one?

Shameless Plug:

Questions?
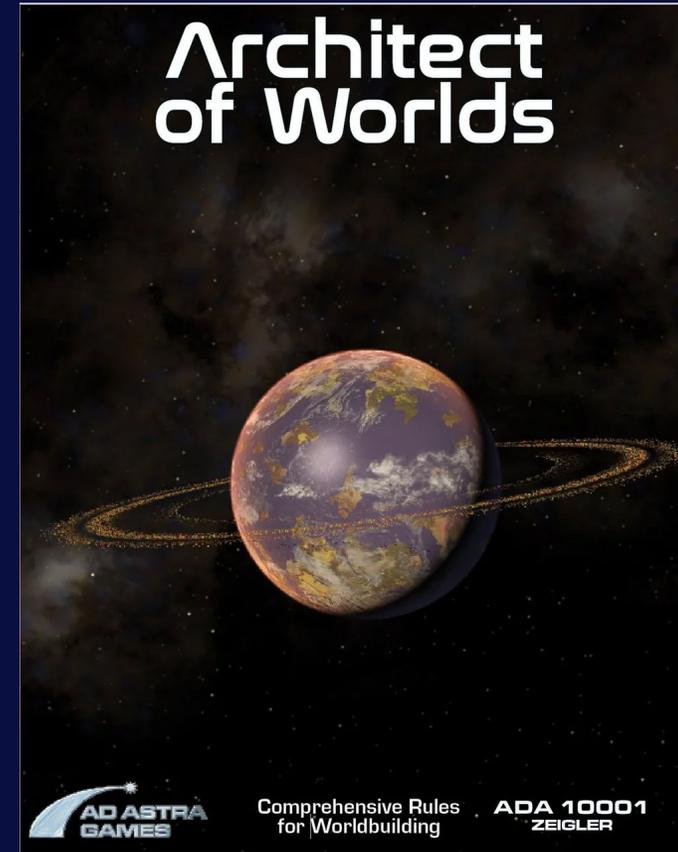
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