HABITABLE PLANETS

For every star with planets, how many of these planets (on average) **are habitable for life? (n_e in Drake equation)**

There are several main requirements:

A. heavy elements (C, N, O, . . .)

Nucleosynthesis: see chap. 1 in textbook for more details.

^{1}H-present in big bang.

^{4}He--during ~ few minutes of big bang, ~10% (by number) produced. [Note: some helium is made in stars, but only ~1%.]

Everything else is made in stars.

1st generation stars can produce:

^{12}C---triple alpha reaction ($3\,^4\text{He} \rightarrow {}^{12}\text{C}$ in cores of red giants)

^{16}O---from $\text{He}^4 + \text{C}^{12} \rightarrow \text{O}^{16}$ in cores of red giants.

The red giants lose mass by winds or explosions, “seeding" the interstellar gas for the next generation of stars.

Heavier elements made by additions of alphas (He), protons, or neutrons (“s-process”) onto these ligher elements, mostly in massive stars which explode as supernovae, scattering newly-formed elements throughout the Galaxy.

^{14}N---comes from ``CNO cycle" (need C+O to start it). C and O are used as catalysts for H→He, but some C+O are turned into ^{14}N.

So ^{14}N can only be made in 2nd generation (or later) stars.

→ Implication for SETI: reject oldest (“population II”) stars. These can be recognized by their spectra (e.g. very weak spectral lines of metals).

But only a very small fraction $\sim 10^{-3}$–10^{-4} of stars are Population II.

[There is now strong evidence that stars with exoplanets have *slightly* larger metal abundances than normal. Some people think this might mean (giant) planet formation is *very* sensitive to metal abundance, but others think it just reflects cannibalism of the (metal-rich) planets.]
[Another, trickier, aspect: Might need lots of *heavier* metals for technology. But whether many of these get to the planet's surface depends on planet's mass, geology,...]

B. **Distance from star** (determines planet's surface temperature)

Temperature should be in range for liquid water (273 to 373° K [0 to 100 ° C] ---we'll discuss alternatives later). The corresponding distance range is called the "**habitable zone,**" HZ, or sometimes "**continuously habitable zone**," CHZ, referring to a planet that *always* has liquid water on its surface.

Water is considered necessary or optimum for life by most people for many reasons: 1. A liquid offers protection from the parent star's UV radiation, and a medium in which the earliest organic molecules could move around and react; 2. Water is nearly unique in its molecular structure, which leads to, for example, ice floating instead of sinking (important!), water's great abilities as a solvent, and several other properties. (To be discussed in next part of course)

Consider Venus and Mars---runaway greenhouse on Venus (because so hot that H_2O stayed in atmosphere) and runaway freezing on Mars (because so cold that H_2O froze, increasing planets reflectivity ["albedo"] . (However many people think that Mars once had liquid water, mostly from the forms of certain surface features but also because its atmosphere was probably much thicker in the past.) So maybe this would have occurred to the Earth if we had been a little closer or more distant from the sun. (Complicated subject—see below and discussion in class.)

Also: "faint young sun" paradox. Sun was only70% as bright when young, water should have frozen. With large albedo of ice, hard to see how it would ever unfreeze. But it's known that earth was covered with significant liquid water 4 billion years ago! (That's the "paradox".)

Proposed solutions: Large amounts of CO_2 or other greenhouse gases, fast earth rotation (only about 14 hr instead of 24 hr, which may have caused less cloud cover), less land, all could have helped.

Michael Hart's early and crude climate calculation: CHZ could be very narrow (0.95 to 1.05 AU), and n_e therefore very small (<<1). In this case we are just very lucky, and life should be relatively rare in the Galaxy.

But more recent climate models yield a wider CHZ. Most people adopt 0.85 to 1.5 AU as CHZ band (based on a seminal 1993 paper). More recent calculations including CO_2 ice clouds {Forget et al. 1997, 98; Mischna et al. 2001} give an outer CHZ radius up to 2.4 AU! Outer limit is extremely uncertain and difficult to calculate (some explanation given in class). But if the CHZ is this big, could have several habitable planets per star.

It's important to understand how the location and size of the CHZ depends on the luminosity (and hence mass, for main sequence stars) of the parent star:

More massive star → more luminous → CHZ more distant (and wider)

Less massive star → less luminous → CHZ less distant (and thinner)

[Note: With a high-luminosity star, the CHZ could be *in* the Oort cloud, which could imply 100s or even 1000s of habitable planets around these stars! However these stars are rare, and don't live long (see below).]

Digression: Extending the definition of "habitable zone"

There is good evidence that water may exist far outside the conventional CHZ: Jupiter's moon Europa (as photographed by Galileo spacecraft) shows evidence for ice flows: tidally-induced geologic activity heats water ice under surface to near-liquid, then gushes through ice crust, "icy volcanism". Surface is much smoother than other Jovian moons, few craters, also suggesting flows. There are speculations that ocean exists beneath surface. We'll briefly discuss a speculative ecology for Europa in Part III of this course.

Some people have even speculated that *most* of the habitable objects in the universe are not planets, but tidally heated moons of planets. {Williams et al. 1997, Nature 385, 234}

C. Size of planet

Too small → no atmosphere (from volcanic outgassing) to form oceans (if that's how they formed), block UV, …

Too large → outgasses massive CO_2 atmosphere, greenhouse effect prevents liquid water (it all stays in the atmosphere and eventually leaks away as UV photons break up the H_2O).

Some rough estimates suggest that habitable planets would have to be within a factor of two or three of Earth's mass! Since planetary formation simulations make planets of a variety of masses, this planet size constraint would make habitable planets much less frequent.

D. Large moon? (See earlier notes on formation of moon.)

Recall that the fact that we have such a large moon (relative to the Earth's size) is a very fluky occurrence, probably involving the chance collision of a large planetesimal, or even planet, with the Earth during the early evolution of the solar system.

We'll see that current ideas on the origin of life may require **tides**. If so, then life requires a large moon like ours ⇒ life could be rare!

Another likely result: the obliquities (angle of spin to orbit of planet—23.5 degrees for Earth currently) of most of the planets are predicted (from detailed calculations) to have huge chaotic variations over short timescales (~ 10 million years). Earth's obliquity would have varied between 0 and about 60 degrees! This might make it tough for life to get started or survive, depending on whether or not the planet has a thick CO_2 atmosphere, how the land masses are distributed, and other factors. {Williams et al. 1998}

But the Earth's obliquity is stabilized by the tidal effects of the Moon, and only varies by about 1 degree or so (and even that might be enough to account for the occurrence of ice ages and other phenomena).

Also, Earth's magnetic field (which protects us from solar flare cosmic rays), and large molten core may be related to our moon's tidal heating. Nobody understands whether other planets should have magnetic fields (except in general terms), or whether having one is important for life.

For detailed account, see Comins, N.F. *What if the Moon Didn't Exist?* (1993)

If any of these factors are important for habitability, this could make n_e extremely small, since the existence of our large moon is a very low-probability event. This could mean ETI is very rare!

E. Giant planets like Jupiter and Saturn? These eject most comets from the solar system. Otherwise, comet impacts with Earth would be about 100 to 10,000 times more frequent, making the climate extremely severe and variable. (Textbook has interesting discussion of this.)

Interesting alternative: It is currently believed that most of the Earth's water was delivered by asteroids that were scattered into Earth-crossing orbits by Jupiter. If no Jupiter, then maybe no water! We already saw (in Planet Formation presentation) the potentially significant effects of the presence of a giant planet and its properties on water delivery by icy planetesimals in simulations.

In 1993, George Wetherill claimed that giant planets should be rare because of observations of disk dispersal time compared to [theoretical] giant planet accretion times (but remember, they could form more quickly by gravitational instability). No matter how they form, notice that planet searches are getting a detection rate of about 5% for giant planets, which would agree with Wetherill's result, and suggest that life on inner planets may be rare! However also remember that the radial velocity technique can *only* detect relatively close-in planets so far, so this 5% is a lower limit. So it's too soon to know whether to give this much weight.

Also remember that we (think we) know that many giant planets suffer **migration**, and if that happens, it may kick a terrestrial planet out of the system. So you may need to have a giant planet whose orbit lies outside the habitable planet's orbit, and which will not suffer much migration. Delicate situation!

F. Stability of temperature

(i) age of parent star---Life took a finite time to arise on earth, maybe 0.5-1 billion years (maybe much less, though). Assume this is typical. So reject stars with mass $\gtrsim$ 1.25 solar masses (these are the higher luminosity stars), because they only live $\lesssim$ 1 billion years. Only ~10% of stars rejected because of this.

This is partly why most planet searches and SETI signal searches are concentrating on solar-like or cooler stars, not more massive stars.

[But maybe we should require lifetimes greater than about 4 billion years, since it took that long for "intelligence" and technology to develop here, and we're searching for life forms with these traits. In that case we should look at even lower-mass (lower-luminosity) stars.

And what we really need is for its *current* age to be large, not just its total lifespan (since we might catch it at any point in its life). So we need the ages of stars on our list, but this is extremely difficult to obtain.]

(ii) binary stars---might be difficult to have stable planetary orbit in a binary system. This rejects ~50% of stars. Another consideration is whether planetary accretion can occur in a binary system. {Whitmire et al. 1998, Icarus, 132, 196}
[But notice that some binary star-planet configurations may be favorable. Bennett et al. textbook give some discussion on this; more in class if time.]

(iii) red giants---changing on time scales $\lesssim 10^8$yr. Rejects~1-5% of stars. [There is a recent proposal to use red giants as a test of how long it takes for life to develop—explained in class.]

(iv) obliquity and eccentricity of planetary orbits. We discussed obliquity above. Obviously large eccentricity would subject the planet to large temperature variations.

G. Can low-mass stars have habitable planets?---Until recently, most people would have ruled out planets around low-mass $\lesssim$ 0.5 solar masses stars (spectral type M stars) as potential sites for life.

Understand the reasoning: low-mass stars are faint, so planet must be very close for suitable temperature; but then get strong tidal effect due to star, which synchronizes rotation and revolution (like our moon). This *might* cause the atmosphere to freeze out, because of lack of circulation, but this is uncertain.

But several increasingly detailed calculations of the atmosphere of a tidally-locked star show that even a thin atmosphere is capable of circulating gas between the light and dark sides, keeping the temperature stabilized so much that you *would* have liquid water. So tidal locking does *not* rule out low-mass stars as parents of habitable planets.

Other potential problems with very low mass stars: strong flare activity, narrow habitable zone, questionable for photosynthesis. Scientists split on whether these are a problem. (I'll explain in class. Your text also has a good discussion of low-mass stars.)

These are clearly important points since low mass stars comprise about 70 to 80 percent of all stars: **If low-mass stars can have habitable planets with life, then they are the most common abodes for life in the universe, and we should be searching for signals from them**. Also, they have very long main sequence lifetimes, so you could have civilizations as old as 10-15 billion years on planets orbiting these stars.

Conclusion: avg. number of *habitable* planets per star ~ 0.01--0.5, with huge uncertainty (mostly due to unknown significance of our moon; also the existence of a Jupiter and the importance of planet mass—these could all make the number much smaller). This is what we called n_p or n_e in the Drake equation. So if we multiply this by f_p (fraction of stars with planets) and then the number of stars in our Galaxy, we get the number of habitable planets in our Galaxy. With great uncertainty, most people think there are *probably a very large number—maybe 100 million to billions of habitable planets in our Galaxy*. This is the motivation for TPF/Darwin.

Another aspect of this: Are there places in our Galaxy that are especially conducive to life, or especially dangerous? If so, there may be a "Galactic Habitable Zone," for example at some optimum distance from the center of our Galaxy. (Example: Metal abundance decreases outward in the Galaxy [so hard to make planets in the outer Galaxy?], but supernova rate [dangerous] higher in the inner Galaxy.

But now the question is: Did they develop life (Part II of course), and did that life develop our kind of "intelligence?" (Part IV of course).