Are we alone in the Universe? Earth is a very special case

Atronomers and astrobiologists have been spotting many exoplanets (outside our Solar System) with some remarkable similarities to the Earth. However, as Yogi Berra's son once said, when asked about how he resembled his father, "Our similarities are very different." Please read on.

I offer this long essay that concludes life is extremely unlikely to be found. It is in the hope of raising the bar in the discussion. The probability of life in the rest of the Universe is very high. The probability that it is very, very far from us is also very high. Reasonable estimates of the probability of any planet being habitable, or, more so, of harboring life, and even more so, of harboring intelligent life, are in the realm of very small numbers. Multiplied by the enormous number of planets, the probability of life is again very high. The closest Earth-like planet found to date is 1,400 light-years away, making for a pretty dull conversation of 2,800-year exchanges of dialogue, even if that almost-Earth supports intelligent life. More likely, the nearest planet with intelligent life is much farther away. We're extremely unlikely to be contacted, which is to be grateful for, given the history on Earth of contacts between cultures of very different levels of technology (it ends badly for the culture of lower technology). Nonetheless, it is exhilarating to look in detail at what it took to make life on Earth, the confluence of many events of low probability.

The search for habitable planets

The search for potentially habitable planets has become a passion among astronomers and among people who call their discipline astrobiology. More than a century back, the possibility of life on Mars was proposed enthusiastically by Sir Percival Lowell, and others took the cue. Recent unmanned missions to Mars have searched for life, at least as microbes. More recently, the search moved farther out, to planets of distant stellar systems. Astronomers have had great success in detecting these planets, particularly with the Kepler telescope. They use the tiny fraction of light loss as the planet partially occults the central star. They can infer the orbits and surface temperatures of these exoplanets and may ultimately measure the constituents of the atmosphere on some of them. Both astronomers and astrobiologists then focus on a habitable zone for a planet, defined by stellar and orbital parameters that should maintain the planet at a temperature constantly in the range amenable to life. Does an equable temperature range alone make a planet habitable? No one claims that, citing the need for a medium such as liquid water (or, much less plausibly, ammonia).

Ah, but there are many more constraints on habitability. Many of them have been presented eloquently by geographer Vaclav Smil of the University of Manitoba in his 2002 book, *Earth's Biosphere: evolution, dynamics, and change* (MIT Press). I recast his fascinating points here and add more, but first, let's look just at temperature and energy together. Moons of other planets in our solar system are a system more readily studied, since we can sent probes to them or near them, measuring not only temperatures but some bits of chemical composition and flows. Astrobiologists wish to get more information about Europa, a moon of Jupiter, Enceladus, a moon of Saturn, and several others. The medium of life, water, might me liquid on these bodies, with flexing of rock by the tidal pull of the giant neighbor raising temperatures raised above the very low values set purely by radiative balance. Flexing or volcanic heating on various bodies could also be a source of energy. However, energy has to flow from a 'source' to a 'sink' to do useful work, particularly to run chemical reactions in the metabolism of an organism, enabling growth, maintenance, and mobility. Energy that doesn't flow just sits there, such as warm water over equally warm water –no overturning, no other motion. On Earth, radiant energy flowing from the Sun to photosynthetic reaction centers in green plants, algae, etc. provides this energy for life. Not all energy flows can do significant work, however; only the fraction termed free energy can do work. Sadi Carnot kick-started our knowledge of free energy in 1824 (in appreciation, the French named a street for him in the city of Aigues Mortes; good on ya', France). There's a lot of free energy flow in sunlight reaching photosynthetic organisms on Earth. Not so for low-temperature heat flows in flexing moons. There are ways to capture a tiny fraction of this 'geothermal' (selenothermal?) energy, such as with a Stirling engine, but organisms don't seem to be able to make one.

There's much more to the story when we consider other factors of biology, chemistry, and physics. Astrobiologists know that certain chemical compounds in a planet's atmosphere can signal the presence of life, but presence isn't enough. Chemical elements have to be recycled from losses to erosion. For building blocks of bodies carbon appears necessary, and to run critical electron-transport reactions the transition metal elements appear to be equally necessary. Also, any atmosphere has a greenhouse effect, but the warming can go terribly wrong in a short time. Earth almost lost its life when early cyanobacterial life liberated oxygen to oxidize methane to carbon dioxide, almost freezing the Earth solid – more on that, later. Venus had the opposite experience, baking away any chance for life, though not the fault of any life on it.

Betting on life out there

In 1961, Frank Drake posited his famous equation for the likely number of planets in our galaxy harboring intelligent life. It's the product of a cascade of probabilities:

Average rate of star formation in our galaxy,
multiplied by the fraction of stars having planets,
multiplied by The average number of planets per star that can support life,
...multiplied by several more factors

The third factor is my focus. Given a planet, is it habitable? Vaclav Smil and many others have addressed he additional factors required for life to communicate over vast interstellar of intergalactic distances. At the end, I offer a few comments on the topic.

I offer in advance my conclusion that, while there may be many instances of life on other planets, the probability of life per planet is so low that the next planet with life on it is very far away. The probability of intelligent life that can communicate with us is far lower, even as Drake admits. We are extremely unlikely to communicate. This still leaves us the opportunity to examine planets elsewhere and see more of the wonder of the Universe.

Getting the temperature fright. Simply, life on Earth needs temperatures that keep water liquid but not too hot, at least part of the time. Certainly, there are unfavorable excursions. Siberia air temperatures reach -60°C; soils in hot deserts reach 70-plus °C. One might object that life around hydrothermal vents along mid-ocean ridges experiences high temperatures that can, for one, denature its proteins, but high hydrostatic pressures at the same locations stabilize protein structure. We then expect life to thrive somewhere between -2°C in cold seawater and hot surfaces pools such as at Yellowstone National Park at 55-70°C. (Those heat-tolerant organisms gave us a heat-resistant DNA replicase that enables so much of modern biology via the PCR method. It's how we know, among other things, that we modern humans have some Neanderthal and Denisovan genes in us, as well as viral genes from way back. We've been genetically engineered by nature.) Outside the equable temperature limits, some organisms can survive sometimes (double "some") by going inactive, as by hibernating. Others create resistant forms such as spores. Humans make some striking acclimations. People live in the Danakil Desert at a routine 50°C.

The great story of coping with temperature extremes is written large in the literature of physiology. A good presentation with mechanistic understanding is in the book, Environmental Physics, by G. S. Campbell and J. N. Norman.

With a diversity of physiological, behavioral, and developmental acclimations enabling organisms to survive and prosper in environments that may reach temperatures that are extreme in our view, it's not possible to set hard-and-fast limits for the livable range, even for familiar Earthly life. That said, there are regimes of temperature in space and time that are real deal-breakers for life and many more regimes that seem to militate against abundant life and, especially, multicellular life and the subset of life that's intelligent. Temperatures should not stay extreme for times longer than the slowest generation cycle of organisms. Orbital physics enters here. A` la the Drake equation, a planet can't be too near or too far from its star to be permanently cold or hot. That's a given. There are also orbits that endow a planet with a good mean temperature but make it too cold or too hot almost everywhere or for too long a portion of that planet's year. A planet tidally locked to face the star is very hot on that face and very cold on the opposite face. Witness Mercury in its 3:2 synchrony with the Sun; the planet rotates to expose different areas to sunlight, but areas stay exposed for 1/2 of a year each. A planet with a severe axial tilt doesn't average out its heat load from the star over its day of rotation. For long portions of its orbit, the poles are very oblique to the star, with temperate conditions. For other long times, the poles face the star at a shallow angle, getting hot, or face cold interstellar space, getting cold. The lower latitudes face these problems, out of phase with the poles. In our Solar System, Uranus has an extreme tilt of 98.5° from the plane of the ecliptic. Exoplanets might have the same problem, which is effectively undetectable from our telescopes. Earth's axis is stabilized by our Moon, which is at a fortunate size and distance to do this...even if it continues to move out slowly.

Orbits set the stage. Orbits with high ellipticity also are likely deal-breakers. Earth moves closer and then farther from the Sun over the year, helping drive our seasons. The difference between the extremes is 3% currently (and it changes over long times, helping explain Ice Ages and more). A 3% shift in distance results in a 6% difference in intercepted sunlight, because radiation falls off as the square of the distance from the Sun. A highly eccentric or elliptical orbit would cause very large changes in radiation interception and, thus, in average temperature of the surface. (If the planet has a stable reflectance, it acts closely like what physicists call a black body. It can only balance the incoming stellar energy over a longer time by radiating thermal infrared out to space, at a rate proportional to the fourth power of the temperature. Some simple math then says that the surface temperature – as absolute temperature measured from absolute zero - varies with the square root of the distance from the star. A planet experiencing a 4-fold change in distance would swing from one low temperature to one twice as high. For a mean temperature of 15°C or 288 Kelvin, such as for Earth, the swing might be from 70% to 140% of this mean. That's 202K, or -71°C, to 404K, or 141°C!)

One more orbital feature of importance is rotation period. Our local planets range from 10 Earth hours (Jupiter, and, close to that, Saturn) to 243 Earth days (Venus). A fast rotation clearly helps average out solar radiation around the longitudes. A very fast rotation is not a problem for energy balance, but a long one is a problem. At any one time, a range of longitudes is facing the star for a long time and is getting hot, and another range is facing the other way and getting cold. Atmospheric circulation helps even out the temperatures, but far from fully. On Earth, the equator-to-pole circulation helps moderate the equatorial and polar temperatures, both, but only partially. The detection of rotation periods of exoplanets is very challenging, so we don't know what fraction of planets have "good" rotation periods. Given the way that angular momentum is distributed among bodies as a stellar system forms, it might be a high fraction.

Staying extra warm. The remaining big factor in setting the surface temperature of a planet is the greenhouse effect of its atmosphere. Earth is 33°C warmer on average than it would be without water and the minor gases, mostly CO_2, that drive the whole setpoint. This brings us to chemistry, which we call geochemistry on Earth. We could coin a term for it on exoplanets - suggestions?

Chemistry as a constraint, or a whole set of constraints

The initial conditions. The chemistry of the surface of a planet is set by the gross composition of the planet and a variety of processes that sort out the various chemical elements. The gross composition is set during planet formation. It owes a lot to the closest supernova that happened sometime before the stellar nebula started condensing into a central star or stars and all the planets. This supernova shot out all the elements heavier than, say, oxygen in a burst of nucleosynthesis. The one that seeded our Solar System gave us the iron for our human blood, phosphorus for our bones, silicon for the skeletons of oceanic diatoms, and the panoply of elements in Earthly life.

The elements, principally in chemical compounds such as silicates or simple organic compounds, sorted out several ways. The gross sorting during condensation into planets left Earth with rocky material, little hydrogen and other light elements, and a lot of heavy metals (including in this term I put the transition metals such as copper and iron). The sorting went on for some time as the Earth solidified. Consequently, Earth has a large core with much iron, though a lot is left in the mantle, fortunately. Heavy elements even now are sinking toward the core, releasing gravitational energy as heat. It's not much, nor is all geothermal heat at about 0.06 watts per square meter, compared with mean solar radiation at the surface of 234 watts per square meter. Nonetheless, it's also a critical heat flow. It drives tectonic motions that continuously renew the surface of the Earth. Large crustal areas, the plates, occasionally dive one under another, but new surface emerges at mid-ocean ridges, bringing chemical elements back to the surface. On smaller scales, volcanoes do the same. Without tectonic circulation from the deep mantle, the land surface would eventually lose life-critical elements. Earth has a large ocean and resulting hydrologic cycle that erodes the surface. Erosion moves phosphorus to the ocean sediments, out of reach of life on land because phosphorus can't come back to land in gaseous form such as carbon or sulfur can. There's an interesting side story here. Our modern agricultural practices use about 20 million tonnes of P each year, mined from deposits such as in Morocco, Florida, and Nauru. (Nauru has almost disappeared from mining, with the residents moving to other places!) We have to move to poorer and poorer deposits eventually, at high energy cost that will be out of economic reach for much of our population. We didn't face this problem in the past because we got our P in crops grown locally and then defecated that P in the same place. Sanitation wins for disease control but not for P.

Keeping elements available. A major constraint for life in the long term is then tectonic activity. It has to continue for billions of years that life likely takes to evolve to stages such as we enjoy (I hope we enjoy it). That requires a narrowed range of mass of a planet. Too small and the planet cools deeply too fast; tectonics never develops or stops early. Mars is now inactive, and apparently dead, certainly never having reached the stage of multicellular life. Too big and the planet may never create a solid surface if it's also sufficiently rocky to make a nice solid home. It may also have its heavy elements sink mostly out of reach of the surface. Some heavy elements should remain, but vibrant life may not be supported. A large planetary mass creates other problems, chemical and mechanical. Small mass leads to a low gravitational attraction, allowing light volatile elements to escape. Earth has kept its hydrogen so that water remains even while solar radiation photolyzes some water to hydrogen. Mars lost so much of its hydrogen that water is no longer present. A large planetary mass leads to strong retention of the gaseous compounds of the original solar nebula. This created the gas giants of our own Solar System, Jupiter , Saturn, Uranus, and Neptune. A deep gaseous atmosphere is inimical to life, at least, life that doesn't float in air and that treads or swims on a surface. The solid surface is buried under a deep atmosphere that greatly attenuates stellar radiation reaching the surface. Also, the greenhouse effect can attain unfavorable magnitudes. I'll have some more comments in the section on energy balance.

Is life only carbon-based? Abundant speculation has been done on alternatives to carbon-based chemistry for life on other planets. Life needs large molecules, the genetic materials and proteins or any analogs that can be constructed. Metabolism needs elaborate biochemical controls, possible only with large molecules with exquisitely attuned chemical properties such as highly selective enzyme activity. Carbon does very well for us, making long chains in hydrocarbons and lipid tails and interspersed with nitrogen and oxygen in proteins, hemes, and nucleic acids. People have proposed life based instead on silicon. Silicon is an analog of carbon, sitting below it in the periodic table, and it can make chain molecules. Silicon and oxygen alternate in silicone rubbers that seal our bathtubs. Silicon-silicon chains are, however, are less stable than carbon-carbon chains. Ask a chemist who has synthesized silanes. They are pyrophoric, spontaneously bursting into flame with oxygen in air. They'd be expected to do the same in any planetary environment that has an energy source in having a strong oxidant (O_2 for us) and a strong reductant (lots of reduced carbon compounds for us, whether fats or carbohydrates). Silicon chains are also not very stable at elevated temperatures. I think we can safely dismiss silicon.

Does it need water? Life requires a liquid medium. Here on Earth, this is water, a highly versatile compound for its ability to support solutions and suspensions of the biochemicals of life, as well as for its physical properties of heat capacity heat of vaporization, dielectric constant, and more. Water has strong hydrogen bonding among its molecules, allowing it to remain liquid at temperature well above those for its analogs with the same molecular mass. Methane has no hydrogen bonding and boils at -182.6°C at Earth's sea-level atmospheric pressure. It's important to be liquid at higher temperatures, because chemical reactions are almost all activated by temperature. A crude estimate for biochemical reactions is that they double in rate every 10°C. Let's compare reactions in methane between its freezing and boiling points, about -170°C,, and in water at 50°C, 220°C higher. The crude estimate is that the reactions run 2^{22} times faster in water, or 4 million times faster.

Water's high heat capacity, about four times greater per mole than that of most other planetary materials or of methane, reduces the temperature swings arising from changes in intercepted solar radiation daily and seasonally. Its high heat of vaporization also contributes, and the latent heat released as water condenses from its vapor drives vigorous atmospheric convection. This convection makes for a robust cycle of precipitation that renews water on the land surface. Water's high dielectric constant reduces the electrostatic attraction between dissolved positive and negative ions, allowing ionic compounds such as salts to dissolve or charge complex proteins to stay in solution.

Maybe water can be substituted by another chemical analog, ammonia, NH_3. This, too, has been suggested. It, too, is problematic. Ammonia, like water, has significant hydrogen bonding that gives it an anomalously liquid range between its high melting point (-77.7°C at normal terrestrial pressures) and boiling point (-33.35°C). This is still pretty cold. The average of the two phase transition points is about -55°C, a factor of 105°C lower than for water. Representative biochemical reactions would be expected to run about 1,000 times more slowly than in water. We run into another problem with ammonia, its greenhouse effect. Let's assume that we want a higher temperature for biochemical reactions. This could be achieved only with higher atmospheric pressures, because the pressure of any substance's vapor rises exponentially with temperature. At a temperature similar to that on Earth, 15°C or 288 Kelvin, the vapor pressure of ammonia is 4 Earth atmospheres. Ammonia is about as potent a greenhouse gas as is water, with strong absorption bands for outgoing thermal radiation at wavelength of 6 and 10 micrometers, similar to those for CO_2 on Earth. Avoiding a runaway greenhouse effect with lethal high temperatures requires that the planet be far away from the star. The radiant energy from the star would be quite weak, then. Also, ammonia but not water is chemically reactive with oxidized compounds. Why is this significant? For our multicellular life on Earth, we rely on oxygen as one endpoint in the reduction-oxidation or redox scale, with reduced carbon compounds at the other end. Biochemically controlled reactions between these endpoints give us our energy metabolism. Now, water as our medium of life is effectively unreactive with these redox compounds. In contrast, ammonia at 4 atmospheres reacts quickly with oxygen and with a variety of plausible oxidants. Oxidation to nitrogen gas would destroy the greenhouse effect on a geologically (exoplanetologically) short time scale.

Adjusting the greenhouse effect over time. It's worth considering more detail about the greenhouse effect on a planet. Planetary temperatures don't stay the same if the stellar radiation doesn't stay the same. Early on, when life was evolving on Earth, the Sun's output was about 70% of its current value. For adequate warmth, abundant methane in the atmosphere provided a much stronger greenhouse effect than now, compensating for low solar radiation. As the Sun's output rose, terrestrial temperatures would have risen catastrophically. Fortunately, another catastrophe cut this short. Cyanobacteria in Earth's oceans released enough oxygen to oxidize methane to CO_2. As noted earlier, this almost extinguished life on Earth, but it set the stage for modern life, both for temperature and the abundance of oxygen as an energetic oxidant for our metabolism. A planet that doesn't have a major transition between types of greenhouse gases in its atmosphere is a problem for life. Life might wait for the era of stronger stellar energy output, though this gives it less time to evolve more complex forms. After all, it took over 3 billion years to get multicellular life on Earth, and that may have been a lucky accident to have the original single-celled life.

Life keeps resetting the thermostat. There's still more about the greenhouse effect. Earth has a thermostat of sorts. Higher temperatures increase the weathering of surface rocks. The reaction of the solubilized rock material with CO_2 in the air reduces the concentration of CO_2 in the air. The greenhouse effect abates and temperatures go lower. Ammonia reacting with planetary rocks may have no such negative feedback. Life gets into the act, again. Higher plants take up CO_2 in photosynthesis, creating their own biomass. Almost all of it ultimately decomposes over the span of months to centuries. Not all of it does. Plants make lignin as a strengthener of their tissues, and lignin is hard for fungi and bacteria to decompose. A small fraction of biomass resists decomposition to become kerogen, a precursor of coal and oil, and then coal and oil. Forests in the Devonian age locked away vast stores of carbon. The long-term history of CO_2 on Earth is that is has been decreasing. There are episodes of increasing CO_2, but the trend is downward. Hence, we have the recurring Ice Ages, in which regular changes in Earth's orbital parameters helped drive the transitions into and out of the ages. Plants have experienced evolutionary selection pressure to do more with less (CO_2, but also water). A new type of photosynthesis evolved about 20 Mya, called C_4. A first biochemical step in acquiring CO_2 from the air has been added, effectively pumping CO_2 to higher concentrations for the "standard" or original C_3 pathway that would run increasingly inefficiently as CO_2 declines. Human activity in the Industrial Age has temporarily (and perhaps disastrously) reversed the trend to lower CO_2 but the long –term trend should remain. Stay tuned.

Those other essential elements. Life on Earth requires a considerable number of chemical elements beyond carbon, hydrogen, and oxygen. We covered a bit about phosphorus earlier, considering its poor recycling on the surface of the Earth other than on a 150-million-year scale of tectonic turnover. Humans require nitrogen, fluorine, sodium, magnesium, sulfur, chlorine, potassium, calcium, chromium, manganese, iron, cobalt, copper,zinc, selenium, iodine, and possibly a few others. Other organisms also need, variously, boron, silicon, vanadium, molybdenum, and tungsten. These have to be available at the surface. The initial surface composition of the Earth, plus tectonic recycling, established the availability of these elements. So, the supernova that preceded the formation of the Solar System was critical, and so was Earth forming in the right place at the right size. All is not favorable, of course. Vast areas of the land are deficient in one or more of these elements. Vast sections of the ocean are deficient in iron that is superabundant in the crust, because iron is extremely poorly soluble in water in an atmosphere with so much oxygen. Reaction with oxygen locked most iron into the red bands of sedimentary rock. Oceans depend in large measure on meager inputs of iron from iron-bearing sand blowing in over long distances from deserts. Deserts have an important function for life, just not as much as for life on themselves.

Energy availability as a constraint

It's radiation. The energy flow from a star to one of its planets is electromagnetic waves radiated outward – visible light, shorter waves of more energy per quantum (photon) in the ultraviolet, and longer waves in the infrared. We may ignore particle fluxes akin to the solar wind or mass ejections, both of which are much smaller energy fluxes around a star amenable to life. Electromagnetic radiation, which I'll simply call radiation for short, has both quantity and quality. First, consider quantity. Assume that most of the radiation heading toward the planet is absorbed. Earth is a beautiful blue marble in space, but only reflects about 29% of the Sun's radiation. Other planets similarly absorb more than 50% of sunlight. Absorbed radiation becomes heat, giving the surface and near-surface atmosphere its major energy input. Energy in is balanced by energy going out as thermal infrared on a rather short time scale. Outgoing energy flow depends on temperature, so that the balance point sets the temperature. The surface temperature is slightly higher than that at the top of the atmosphere (e.g., Mars) to massively higher (Venus), from the greenhouse effect.

Quantity. The quantity of radiation ultimately determines the metabolic energy budget of life on the planet. On Earth on land, about 0.3% of solar energy reaching the surface gets turned into energy embodied in plant growth. Some of it passes through herbivores, and virtually all of it get liberated back to heat as biomass decomposes. The quantity of radiation per unit area hitting the planet is directly proportional to the energy output of the star and it falls off as one over the square of the distance from the star. luminous star is good for energy available to life, with some caveats about having the right distribution by wavelength, as touched on next. Mars could support a fair amount of vegetation in a greenhouse, while life on Uranus would be pitifully sparse even with adequate artificial heating.

Quality. Radiant energy has quality, too, because it is quantized into small discrete packages, the photons. To drive a photochemical reaction as in photosynthesis, the energy of a photon has to precisely match the energy of a transition in the molecules of the reaction center. Energy per photon is proportional to the frequency or inversely to the wavelength. Quantum selection rules are important, too. Were a molecule to absorb two photons, each with half the energy required for a photochemical reaction, the reaction could proceed. However, two-photon absorption is highly disfavored by quantum mechanical rules. Thus, the star's radiant output must be in the range of wavelengths that give the photons enough energy to drive photochemical reactions.

Stars emit light at all different wavelengths and associated photon energies. The distribution among wavelengths or energies is very closely that of what physicists call a black body. In a black body, the distribution of energy among components that can potentially emit radiation is in a unique equilibrium, more properly a steady state. All black bodies have the same shape of the energy distribution, as number of photons emitted each unit of time versus the energy of the photon (or wavelength). What varies is the overall energy scale. The average or the peak energy of the photons is directly proportional to the temperature of the body. Thus, the Sun emits radiation with a peak intensity in the yellow, near 550 nm. (The peak depends upon whether we plot energy vs. wavelength or energy vs. photon energy.) A star twice as hot emits radiation with a peak in the far ultraviolet, at 275 nm. This is not a good star to live near!

Life on Earth is comfortable with radiation coming from a star with an effective temperature of about 5600 Kelvin (K), near 10,000°F. Photosynthetic higher plants that provide the principal support for the rest of us use radiation in the range of 400 nm to 700 nm. How would life on an exoplanet fare near cooler or hotter stars with different peaks in their spectra of radiation?

For a point of comparison, some bacteria use low-energy photons with wavelengths near 900 nm. This is in the near infrared, well below the cutoff for human vision. This lower limit for a photochemical reaction is not a quirk of Earthly life. Rather, it reflects the energy of chemical bonds. Bonds that can be broken by less-energetic photons capture too little energy to drive all the energetic chemical reactions in living cells. Among the fundamental reactions are those that make or break carbon-hydrogen or carbon-oxygen bonds. A single photon with sufficient energy to break these bonds has a short wavelength, in the ultraviolet. The challenge for life was to live near a star, our Sun, with very little output at short wavelengths in the ultraviolet that would damage its proteins and nucleic acids but to use lower-energy photons incapable of directly driving key biochemical reactions. Organisms then pool the energy of two or more photochemical reactions, storing it in intermediate metabolites, and applying it in all other biochemical reactions under very stringent regulation. Green plants and cyanobacteria have two separate photochemical reaction centers, passing energy as electrical potential for reducing CO_2 from one to the other. Organisms that could pool lots of even less-energetic photons emitted by a brown dwarf are extremely unlikely to have evolved. Note that the coupled photosystems in plants rely on transition metals for transporting electrons, and so do many other reactions in cells. From this comes the universal requirements for metals such as manganese and some special requirements for other elements such a molybdenum. Chemistry is intimately tied to energy use.

A long-term supply. The planet can support life if the radiant energy supply is fairly constant. This places another constraint on the type of star. Stars with major variation in output, such as Cepheids, are a deal-breaker. The central star also has to have rather stable output for a long time. While life on Earth might have evolved in perhaps half a billion years, it took another 3-billion-plus to get multicellular life. Main-sequence stars are the place to look for life. Our Sun is a G-class star with a lifetime of about 10 billion years, one of those billions still to go with conditions suitable to support life. Large, bright stars of the O, B, and A classes burn up too fast, as well as having more ultraviolet light. Binary stars, found to be the most common type, are problematic for the variation in total output as the two of them attain varying distances from a planet that close enough to stay warm. They also pose problems of instability of the planet’s orbit.

Keeping away from colliding bodies and other energetic neighbors

Craters and more craters. When I was a boy, I thought, not uniquely so, that the Earth is near the Moon, so why doesn't it have craters all over. Scientists learned, of course, that Earth has been hit nearly as much as the Moon by bodies up to the size of asteroids and comets. Hence, the tale of the iridium layer, the submerged crater at Chicxulub, and the demise of the dinosaurs (the last with some help from massive volcanic eruptions of the Deccan Traps in India). There is a fairly regular distribution of objects colliding with Earth and causing havoc for life. Big objects the size of the K-T boundary asteroid may hit about every 150 My on average. Dust grains hit all the time. Life has come back, if by the thinnest of margins, from the very big impacts. Evolution, once rolling, can build the diversity of life back up so that various layers of producers, consumers, and decomposers end up supporting a fairly stable biosphere after a delay. Too frequent catastrophic events, or events that are too big, could overwhelm this reestablishment. What kind of structure in a stellar (solar) system minimizes the chance of collisions that are too big, too frequent, or both? We certainly have woefully inadequate data on other stellar systems to answer this question. Dynamic models could help answer it, though the question has to be phrased in a way that can be answered – What do we mean by structure? Number and sizes of planets? Elemental composition of the original stellar nebula? I leave this question and its answers to the modelers of stellar systems.

Sterilizing radiation. Neighbors that emit potent gamma radiation are a threat to life, though not a deal-breaker for most stellar systems and their planets. Explosions of stars as supernovae create massive fluxes of particles and gamma rays, and some of our distant neighbors can "go supernova," the equivalent of "going postal" among humans. The nearest star to Earth capable of this is Spica, 265 light-years away. That's to far to give us much radiation; nothing much farther than 50 light-years away would be noticed. How many other potentially habitable stellar systems are this fortunate? One needs to know the density of supernova candidates in space, which I do not. Gamma-ray bursts are not a significant constraint for life, I hazard as a guess.

Intelligent life is easiest to evolve on land – continents are a good feature

Yes, life on Earth evolved in the ocean and progressed to complex animals (oddly, not to significant "plant" life; most of the photosynthetic life in the ocean is single-celled). Life made the transition to land only about 400 Mya. There is intelligent life in the ocean, to be sure. Cetaceans, the whales and dolphins, are often cited. However, their ancestors evolved on land. They are not fish. Their intelligence is also overrated, as recent analyses show. In any event, it's hard to imagine intelligent life in water operating an electronic communication system, the only type suitable for long distances. At its simplest, this is the argument that you shouldn't play a radio in a bathtub. So, a planet for intelligent life that can communicate over long distances should have continents. The Earth had little or no continental mass at first, being a watery planet. Large crustal segments with lower density than the mean had to aggregate and lift up hydrostatically. The first small continents likely appeared at the end of the Hadean Era around 4 billion years ago. They grew to near the current mass long ago, via plate tectonics. I've already cited the need for plate tectonics for a planet to have a (modest?) chance of evoving life. Given plate tectonics, are continents guaranteed to form? I'm not a planetary geologist, but I again hazard a guess that they are so guaranteed.

Conclusion: I do think we are alone

If you're in the market for a habitable planet:

- Pick a good earlier supernova in the neighborhood, but no recent ones. Make sure it made enough heavy element
- Look for one near the size of Earth
- Make sure it rotates and orbits “nicely”
- Its star needs to be near the Sun along the main sequence, long-lived and not too hot
- Watch out for close neighbors that might chaotically perturb your planet’s orbit
- Put your trust in carbon and water
- ...and don’t expect you’ll find one in a sample smaller than many billions. That is, don’t expect you’ll see one; we’re not going to get those billions of samples

I have the overweening conviction that we are alone, in the sense that we will never make contact with extraterrestrial civilizations while our civilization lasts. The extensive set of constraints on life I have just elaborated makes the chance of life evolving on any planet extremely small. There are likely many planets in the Universe with life on them, but they are far between. The chance that any are near us is exceedingly small, and even lower is the chance that any of them harbors life capable of communicating with us...and interested in doing so.

I admit that not all of the constraints are extremely restrictive. For one, low energy inputs could support slow life (maybe not intelligent life). Taken all together, however, the chance of any life remotely like that on Earth looks very, very small. Referring back to the title, I put the chance at far less than anyone’s chance of winning the Powerball Lottery. The chance for intelligent life that communicates over interstellar distances is even tinier. Remember, in the Drake equation there is a factor for how long an intelligent civilization would broadcast signals. These have to be astoundingly energetic signals to cover interstellar distance...and what would be the point for the originators? The average lifetime for a whole species on Earth is only about 2 million years, less than 1/2000 of the age of the Earth. Civilizations are even more ephemeral. Many discrete civilizations have come and gone, Sumerians among the first and they only originated about 7500 years ago. There are many cogent arguments that resource-intensive civilizations such as we have become rapidly destroy their resource base and, with it, their ability to communicate and their own existence. I recently found the wide-ranging free thought of Yuval Harari in his 2014 book, *Sapiens*, in which he expresses cautious optimism at the end, but after explicating copious social processes, many of which militate against our continuance. Again, stay tuned!

Is the search worth the effort? My take on what we’ve learned about life and the conditions that led to it can be summarized in a few sentences. Look up at the stars and wonder. Enjoy the ride. Keep the Earth turning, figuratively.

Regarding the searches for exoplanets, I deem it of some value, if far from my highest priorities. I wouldn’t sell it as a search for life on other planets. As with other basic science, it can tell us a good deal about our place in the Universe. The effort is akin to planetary geology studies on other planets in our own Solar System, similarly informing us about our unique place in the Universe. We’re not going to reengineer the Earth with what we’ve learned. It’s more like art, or for a closer analogy, I cite the testimony of physicist Robert Wilson before a Congressional committee to defend the building of the Tevatron particle accelerator at Argonne National Laboratory. Asked what the Tevatron contributed to national defense, he replied that it gave the nation something worth defending.

Thanks for your patience and interest in reading this.

Note: For readability, I have avoided the academic style of inserting references and footnotes. If this essay develops traction and readers want scientific references, I will insert these.

Note, SETI, the search for extraterrestrial (ET) intelligence: A number of groups, including the eponymous group and other amateur societies advocate for SETI and set up hopeful monitoring systems. I don't take this as a productive effort, for two major reasons. First, the energy burden on an extraterrestrial civilization (let's call it an ETC) to broadcast its existence would be enormous for no apparent benefit, and, second, it's dangerous to advertise our existence.

Consider the energy cost, first. The shortest communication distance, as for us to Barnard's star, is about 4 light-years. Radio waves broadcast with a certain power get spread over a vast area at increasing distances from the source. Intensity (as flux per unit area) decreases as one over the square of the distance traveled. How weak can the signal be at the Earth and still be detected? This will tell us how much power has to be put out at the other civilization's planet. The most dramatic example of communication with very low radio power that I know of is our communication with the Voyager space probes, with Voyager 1 now at 19.5 billion km from Earth (about 12 billion miles in old units). Voyager 1 is broadcasting with 23 watts of power. A very large antenna on Earth, such as at Goldstone in California or Woomera in Australia intercepts a tiny fraction of this power. Detection is still reliable, at a very slow rate of data transfer (Claude Shannon brilliantly proved that the noise won't overwhelm any weak signal if we send that signal slowly.) We might assume that practical communication (if very, very slow) might work 10 times further out, which is about 40 billion km. This is only 1/50 of a light-year. Communication is only working because 1) we know exactly where to point our antennas, with excruciating precision and 2) Voyager knows where to aim at us. An ETC knows nothing about where to expect a receptive civilization. Suppose that they are as good as we are at aiming broadcasts and reception, so that our antennas have to receive from the ETC only as much power as we get from Voyager. Suppose, also, that they have put all their hopes on us as the nearest star system, 4 light-years away. The distance covered is 200 times larger than the distance to Voyager, so they'll need 40,000 times more power (200 squared). That's near one megawatt, not a big burden yet. However, they would be wise not to put all their eggs in one basket and aim at other stellar systems. Each one adds an energy cost, and the cost to more distant stellar systems rises again at the square of the distance. We're still assuming that 1) very, very slow communication is acceptable, or else much higher power is needed and 2) that they know which communication mode we will accept and interpret properly (AM, FM, PWM, etc.) and which carrier frequency we will listen to.

Maybe the communication power and mode are problems that we and they can deal with. The other factor for the ETC is, What do they stand to gain by communicating with us or any other civilization? Ignoring all problems of translation and culture, there is the problem of the response time. That's over 8 years at the speed of light between us and Barnard's star, and even longer for more distant stars. At very low bit rates of communication, a reasonable exchange of a number N of messages takes N times longer.

A very cogent objection to searching for communication with an ETC is that any civilization more technologically advanced than another has had tragic consequences for the other civilization. That's Earth's history many times over – the succession of Mesopotamian civilizations, the contact of Europeans with every indigenous culture in the Americas, perhaps even modern humans with Neanderthals. Renowned physicist Stephen Hawking warned in a documentary aired in 2010 that "If aliens visit us, the outcome would be much as when Columbus landed in America, which didn't turn out well for the Native Americans."

The probability of contact with an ETC is nearly infinitesimal, and a contact is overwhelmingly likely to be successful for them and not for us. Given the first factor only, SETI is probably a harmless exercise. It may have peripheral value in getting people interested in the splendor of the Universe, if their minds are open to all the other possibilities of exploring our place in the space.

[Send to Kurt, Jason, Lynn Neakrase for initial comments]

To add:
Hawking reverses course, teams up with Russian billionair Yuri Milner
Near-twin Earth found...though at 1400 light-year away!
Lee Billings' book, Five Billion Years of Solitude – any content I should be aware of?

Author [Billings, Lee, author.]

Title **Five billion years of solitude : the search for life among the stars / Lee Billings.**

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Kepler telescope image: http://www.space.com/30053-kepler-exoplanet-discoveries-earth-twin.html
Transit method for exoplanets: http://planetquest.jpl.nasa.gov/page/methods
There are other methods: Doppler shift of starlight; direct imaging using a coronagraph; astrometry, detecting the small shift in the star's position

From Jason:

Vince, thanks a lot for this nice exposition. I finally had time to look at it seriously. I probably agree with your final conclusions about communication. There are a few things you might want to add that could make it more convincing/complete, as you see fit. If these are in your document and I missed them, sorry!

- Age: Planets evolve, and so habitability can fluctuate over time. If someone on another planet visited Earth 700Myr ago, when it was covered in ice, s/he would have kept on going. You kind of touch on this in your eccentric orbit point, but in this case it's a bit different. B fields likely change over time too.

- Water: Earth is kind of special here, I think. It's mass in water is near 10e-3 the planet mass. That amount is likely a function of the timing of formation and what got scattered into Earth's orbit from Jupiter's orbit that contained water. You can imagine that that number could be much smaller, or much bigger too.

- Topology: Related to the water point. Earth has coincidentally the property that the height of mountains and the depth of oceans are about the same, so there is dry land and wet land. You kind of touch on this too. But again, the amount of water determines this to a large extent, which I think is a very variable number.

- In general, for context, you might want to add some of the extrapolated Kepler results of the # of exolanets in the MW that are likely terrestrial. I don't have that number at hand, but I believe it was in the tens of billions.

You asked about supernova density, I think it's a few/year across the whole galaxy. That's also a function of time.