SPACECRAFT EARTH

A GUIDE FOR PASSENGERS

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The Spacecraft: Planet Earth

Our understanding of the universe has grown steadily since the invention of the telescope 400 years ago. But less than 100 years ago, we did not even know for sure if the Milky Way was the only galaxy. Now, we know about hundreds of billions of galaxies! From a distant vantage point, the large scale structure of the universe would look like a vast web, composed of clusters and superclusters of galaxies, with huge voids between them. One of the clusters is a special one to us, called the Local Cluster. Within that cluster, one galaxy stands out in our minds: the Milky Way. Within a spiral arm of that galaxy, a very special star carries a family of planets around it: our solar system. And within that solar system is one planet with all the right conditions for life. That planet is our Spacecraft Earth, giving its abundant variety of life-forms a first-class ride through the universe.


NASA/JPL

Figure 1-1. **Pale blue dot**

Planet Earth (bright speck in the center) as seen from the edge of the solar system. Photo taken by Voyager 1.

In the big scheme of things, the earth might appear insignificant. It's such a tiny speck, that even from the orbit of Pluto it would attract little notice. Be that as it may, there are more ways to measure significance than mere size. Our solar system has some very remarkable features: among them, a safe location in the Milky Way, a stable star, and a habitable zone far from giant planets. These features, and others we will consider briefly, are—as far as we know—actually quite rare. For instance, other planetary systems we've discovered around other stars look nothing like our solar system. Their giant planets often are found orbiting very close to their host stars, even closer than Mercury is to our sun. Earth could not coexist with one of those 'hot Jupiters' were our sun's family to follow that pattern. Fortunately, the sun's habitable zone is occupied with one (and only one) planet in a stable orbit with the perfect combination of features to permit complex life.

As audacious as it might sound, I would venture to say that the earth is a unique body in the whole universe. It contains all of the chemical and physical features that are necessary to allow life to exist. To date, there is only one place we know of in the entire universe that has life—and we are riding on that spaceship right now. The improbability of finding another planet as life-friendly as the earth becomes evident when we start considering the many requirements for life. Whatever feature of the earth one is willing to consider in detail appears to be uniquely tailored to promote the existence of not just any life, but large, complex organisms like human beings. In this chapter, we will consider just a few.

Now, I realize that there are all sorts of conjectures about life on other planets and on planets around other stars, but I would submit that even if life were discovered on Mars, Europa or Titan—some of the leading candidates for life-permitting habitats beyond earth—those objects could in no way provide the kind of support systems where life could flourish. At best, only microbes might exist, buried deep under the Martian soil, swimming several miles down under the icy crust of Europa, or frozen in perpetual darkness in a Titan lake. How different from Spacecraft Earth! Indeed, there are very few places on earth where life is *not* thriving in abundance. What accounts for the difference?

Construction

Let's start with the chemical and physical composition of the earth. Life as we know it could not exist in significant numbers if the chemical and physical parameters that characterize the earth were changed even by a small amount. For instance, complex life needs oxygen enough to breathe, but not so much that wildfires would become more prevalent and catastrophic. The right balance is maintained by marine organisms in a sophisticated feedback loop. Responding to the amount of phosphorus eroded from the continents, oceanic microbes bloom and produce more oxygen if levels drop. When there is too much oxygen, other organisms deposit the excess phosphorus in the deep sea sediments.[1]

Examination of the chemistry and composition of the earth shows numerous factors conducive to life—whether it be an abundance of water, a gaseous oxidizing atmosphere, or the availability of necessary chemical elements. We'll hear about bromine in the next chapter, an element only recently found to be essential. That's just one of 28 elements out of the 92 naturally occurring elements that must be present near the surface of the earth in sufficient quantities for multicellular life to flourish. Even some so-called 'trace elements' have been shown to be important for animals and plants.

Here's a particularly notable instance at the atomic scale. As most people learn in chemistry, most substances, when they change from the liquid state to the solid state (that is, when they freeze), become more dense. As a result, whether the substance is iron or candle wax, when the liquid and solid forms are added together, the solid sinks to the bottom. There is a rare exception to this rule: water. It also happens to be the most abundant molecule on the surface of the 'water planet,' the earth.

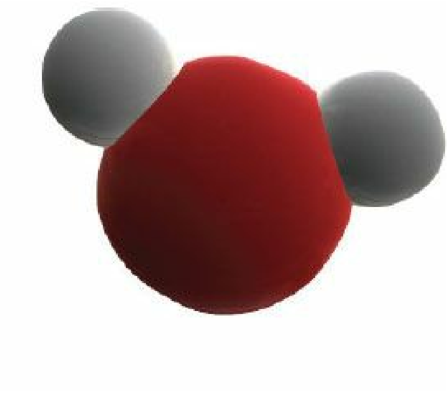

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Figure 1-2. Mouse ears

Molecular diagram of water—one part oxygen, two parts hydrogen

The water molecule is a remarkable device. It consists of one oxygen atom and two hydrogen atoms, the familiar 'H_20.' Electrical forces between the atoms bring the two hydrogens closer together, where they stabilize at an angle of 104.5°, giving the water molecule a 'mouse ears' shape. This conformation is critical to water's unique properties. It explains the highly unusual fact that when water freezes into ice, it expands. As crystals of ice form, the 'mouse ear' molecules arrange into more open structures, or lattices, than they normally would. Because of this expansion, ice is less dense than water, and it floats! This property is vital for life on earth.

Consider what would happen if ice did not float. In winter, water would freeze and sink to the bottom of lakes, rivers, and the ocean, accumulating into increasingly thick layers of ice. The warming summer air would not penetrate those deep layers. Only some of the ice at the surface would be able to melt, resulting in shallow ponds of water on top of deep, perpetual layers of ice. Over the course of time, almost all of the water on earth would freeze. True, there could be a couple of centimeters of liquid water on top of the ice on a hot day, but without abundant liquid water on the earth in oceans and lakes, life would have a most difficult time surviving. There would certainly be no significant life existing in shallow bodies of water if the bottoms were frozen. But because ice floats, much of the water underneath can stay liquid, allowing fish to survive under the ice of many lakes (that's why ice fishing is popular in many high latitudes). Without this unique property of the water molecule, Spacecraft Earth would likely turn into a giant snowball. This is due not only to the shape of the water molecule, but its specific heat—its ability to store much more heat than most other liquids.

Water gives up a great deal of heat when it freezes. It therefore takes considerable heat to melt ice in bodies of water. The heat required to melt ice at zero degrees Celsius (0°C) is 80 calories per gram. This means that to melt one gram of ice would take one gram of water at 80°C, and the result would be two grams of water now at 0°C. So, water of just a few degrees above the temperature of ice melts very little.

Why does water behave this way, becoming less dense when it freezes? The answer lies in the 'hydrogen bond'—a chemical property that received considerable attention from Dr Linus Pauling, recipient of two unshared Nobel Prizes, and one of my mentors at Caltech. Dr Pauling noticed a strange, unexplainable attraction between the hydrogen atoms in adjacent water molecules that causes them to line up in remarkable ways when water freezes. Because of this, the molecular structure stretches out slightly, thus producing lower density in the ice. So simple a molecule, but so profound! To this day, chemists have not explained all the remarkable properties of water and ice. Time would fail us to explore its many other unique life-enabling properties. From the glory of a snowflake[2] to the global water cycle, this clear, beautiful substance graces our photographs, brings laughter to children at the pool, and courses through every cell in our bodies. Life would be inconceivable without water. That's why most astrobiologists consider liquid water to be a requirement for any habitable zone anywhere in the universe.

Another unique chemical element is carbon. Because of special characteristics of the carbon atom, it can form all sorts of combinations with itself and other atoms to form what are called 'organic compounds.' There are literally millions of different chemical combinations possible. The very name 'organic' comes from the fact that carbon is the basic building block of all living organisms, although many organic molecules are not involved in life.

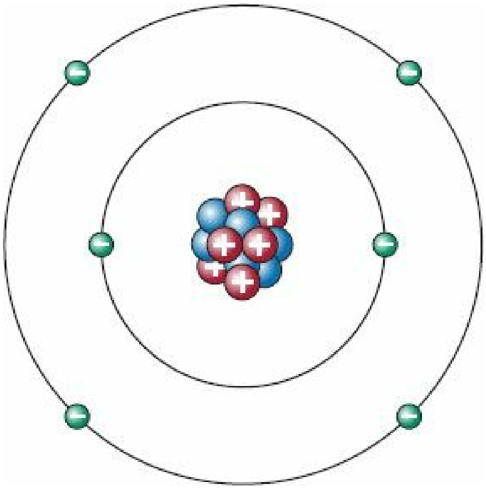


Figure 1-3. Carbon atom

The unique chemistry of carbon makes it ideal for use in living things.

Compounds of carbon include acids, esters, alcohols, and many, many other kinds. In our bodies, the carbohydrates, fats and sugars we consume are all carbon compounds. Carbon is found in the amino acids that combine into proteins and enzymes that make up our skin, blood, organs, arteries and veins, and everything else that gives our body structure and function. Carbon is found in the nucleotides that combine into DNA that stores our genetic information. Most astrobiologists would concur: no carbon, no life. No other element has the ideal properties of carbon. Some science fiction writers have tried to imagine life based on silicon. In the real world, though, silicon tends to form rocks, not the pliable, flexible forms we see in carbon-based life. Life needs carbon. Fortunately, this also is found in abundance on Spacecraft Earth.

Environmental tolerances

Let us consider the physics of the earth. One of the first considerations is temperature. Earth experiences a narrow range of temperatures that is rare in space. We think we know what unbearably hot or cold days feel like, but the universe experiences highs in the millions of degrees in the interiors of stars, down to near absolute zero on some lonely, dark, isolated planets. Temperatures at the surface of earth range from -128.6°F (-89.2°C) at Antarctica to 134°F (57°C) in Death Valley, but those are uncommon. Most of the biosphere never experiences those extremes. Some microbes are even adapted to living in the near-boiling waters of hot springs. Whole ecosystems have been found at scalding hydrothermal vents at the bottom of the sea, where nearby fish swim in cold, perpetual darkness. But those are exceptions; most plants and animals live within a narrower band of the already-narrow set of temperatures on earth. Within earth's more common temperature ranges, we see plants and reptiles thriving in deserts, plants pushing their new leaves up through the snow, and gibbons swinging from branch to branch in tropical jungles. What an amazing world is our home!

There has been much concern of late regarding the fate of the biosphere if average global temperatures were to rise. Concern about the existence and effects of what are called 'greenhouse gases' have received international attention. Alarmed scientists worry that just a few degrees rise in average global temperatures could have drastic consequences on life by melting polar icecaps, raising sea levels, inundating coastal areas, and rendering farmland unproductive with severe droughts. In the past, other climatologists have worried about the prospect of another ice age. The fossil record shows past excursions of higher and lower temperatures on parts of the earth. The fact that life has endured past climate swings suggests that the earth has 'feedback' mechanisms to keep its temperatures from deadly extremes. Some climate models show, for instance, that an increase in temperature would increase cloud cover, which would have the effect of reflecting more of the sun's energy back out to space. As important as these concerns are, we should not fail to recognize that they imply that earth's climate is finely tuned to support the biosphere.

Earth's temperature is determined, to first order, by our type of star and our distance from it. You can 'count your lucky star' by considering our sun's remarkable properties. Fortunately for us, it is one of the most stable, predictable stars known. Occasionally we hear worries about flares and 'coronal mass ejections' that threaten our electrical grid and satellite communications, but the sun's bad days are mild compared to the angry outbursts from the majority of stars. 'Superflares' from red dwarf stars, the most numerous type, would quickly fry any life on a planet in its habitable zone. Many giant stars, at the other end of the size scale, emit so much ionizing radiation, they would render their planets sterile.

Our sun emits a 'solar constant' (energy received at earth's surface) of 1.361 kilowatts per square meter. At solar maximum (the period in the sun's 11-year cycle when its activity increases to its highest level), the heat received at the earth increases by just one tenth of one percent—an extremely slight difference. One of the longest running scientific observations ever made of the sun measured only 0.06% variation from the solar constant over a 32-year period.[3] That makes our sun one of the quietest among quiet stars. Without a predictable energy supply, life would only survive under great duress—not just because of the variations themselves, but because of the aftereffects they would initiate, some perhaps irreversible. If the atmosphere were ever stripped away during a severe solar outburst, for instance, it might never come back. If earth froze solid during a cold period, on the other hand, it might remain frozen thereafter. It takes the right kind of star—a very predictable, reliable one—to support life.

The properties of earth, too, determine its temperature. When we tune in to weather forecasters giving us the predicted highs and lows for the day, we don't usually have to worry about dying from heat or cold, provided we dress appropriately. Even on the most extreme weather days, the highs and lows are very mild compared to what they could be. We can tell by looking at the moon next door. Without an atmosphere and crust like ours, lunar temperatures rise and fall rapidly and severely. Under direct sunlight, the moon heats up to 253°F (123°C), but then drops down to -243°F (-153°C) at lunar night. The Apollo astronauts had to land, do their work, and leave during narrow orbital windows when it was safe. Even so, their spacesuits had to carefully control body temperature, as well as supply oxygen. They could not have survived for a minute without bringing a bit of earth's habitat with them to surround themselves. Even a small leak could have proved fatal. Some of the astronauts remarked about how intense the glare of the sun was without an atmosphere. Had charged particles from a large solar flare come at them while they were on the surface, they would have died in minutes—because the moon has no protective magnetic field. That's another factor that protects life on earth. We will not take the time here to discuss it in detail, except to say that space travel is like wandering through a cosmic 'shooting gallery' when you move outside the earth's protective magnetic field. This is of grave concern to planners of future Mars missions, when astronauts would be exposed to the solar wind and cosmic rays for three years at a time or more. Of the inner planets, only the earth has a magnetic field large enough to protect its inhabitants. (We will consider the magnetic field in more detail in Chapter 7.)

Why the difference in temperature extremes between two bodies, the earth and the moon, at the same distance from the sun? The answers are in the properties of our atmosphere, oceans, and crust. Each plays a part in absorbing, reflecting, and radiating heat according to well-known laws of thermodynamics. The atmosphere filters the sunlight, keeping out the deadliest ultraviolet rays but letting in the 'rainbow spectrum' of colors most useful to plants and animals, with energies just right for photosynthesis and for chemical reactions in cells. The oceans absorb vast quantities of heat and release it slowly, setting up atmospheric and oceanic currents in a glorious dance that circulates the energy to all parts of the globe. The continents, mostly silicates and carbonates, possess enough 'thermal inertia' to store and release energy slowly. These factors moderate earth's temperature to avoid extremes.

Habitability

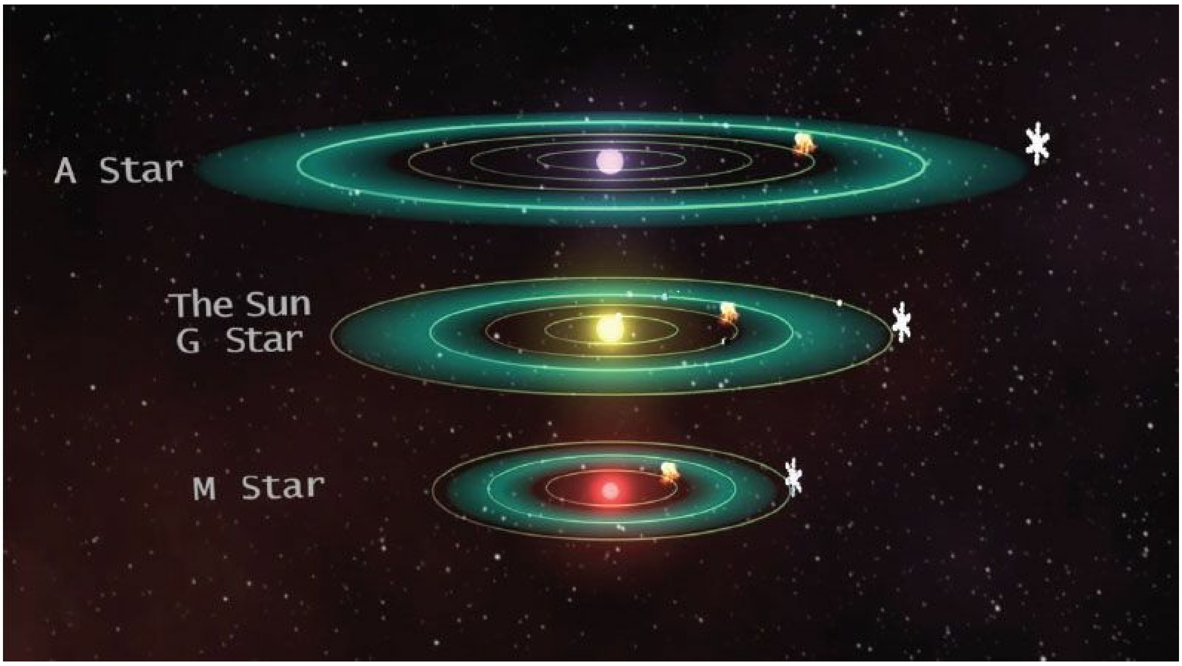
A 'habitable zone' is the orbital radius around a star where liquid water —and presumably life—could exist. As we shall see, there's a lot more required for life than just being 'in the zone'. Earth's distance from the sun —ranging from 91.4 million to 94.5 million miles (average about 92.9 million miles or 150 million kilometers)—keeps it always within the habitable zone. That zone is pretty narrow. Venus is well outside the inner edge and Mars is outside the outer edge. If the Earth's average distance from the sun were 5 percent greater (some astronomers estimate just 1% greater), temperatures would drop such that most of the Earth's water would freeze in a 'runaway ice age.' If the Earth were just 1 to 5 percent closer to the sun, on the other hand, the polar caps would melt, more water would evaporate, and a 'runaway greenhouse effect' would ensue, turning Earth into an inhospitable hothouse.

But that's just one of the numbers in the 'cosmic lottery' that Spacecraft Earth got right. More thinking about habitable zones has added further requirements. From the literature of astrobiology, we can identify ten or more other 'zones' required for habitability, in addition to circumstellar distance:

- **Galactic Habitable Zone:** the solar system must occupy a narrow band within the galaxy.
- **Continuously Habitable Zone:** the habitable zone must not vary significantly.
- **Temporal Habitable Zone:** the habitable zone must last long enough for life to persist.
- **Chemical and Thermodynamic Habitable Zone:** the planet's chemistry and heat transfer mechanisms must permit liquid water to

persist.

- **Ultraviolet Habitable Zone:** the planet must filter out ionizing radiation from its star.
- **Tidal Habitable Zone:** the star must not tidally ‘lock’ its habitable planet to force one hemisphere to always face the star (this rules out most planets).
- **Obliquity Habitable Zone:** the star must not ‘erase’ its habitable planet’s tilt through tidal forces. (While not eliminating the possibility of life, a planet without a tilt would have no seasons, drastically reducing its habitable surface area.)
- **Eccentricity Habitable Zone:** the planet must have a nearly circular orbit so that it stays in the zone.
- **Stellar Chemistry Habitable Zone:** the star must have the right chemical composition to remain quiet and well-behaved. A G2 main-sequence star like our sun is ideal.
- **Stellar Wind Habitable Zone:** the star must not be given to extreme ‘space weather’ that might strip off a habitable planet’s atmosphere.
- **Inhabited Zone:** in 2014, two astrobiologists suggested that to be habitable, a planet needs inhabitants! “…there is a growing amount of evidence supporting the idea that our Planet will not be the same if we remove every single form of life from its surface,” a news report said.[4]



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