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The Universe Awaits

> Space is big. You just won't believe how vastly, hugely, mind-bogglingly big it is. I mean, you may think it's a long way down the road to the chemist's, but that's just peanuts to space.
>
> —DOUGLAS ADAMS, *THE HITCHHIKER'S GUIDE TO THE GALAXY*

Until the early 1990s, the only people who were sure there were planets circling other stars were science fiction fans who witnessed Captains Kirk, Picard, Janeway, Sisko, and others visit strange, new worlds each week on television or thrilled as Luke Skywalker and Princess Leia restored order in a galaxy far, far away. Okay, not really, but I'm not far off. Until then, astronomers were fairly confident that planets circled other stars, but there was no direct evidence of their existence—only the assumption that our solar system was not unique among the many stars that populated our galaxy, the Milky Way, and the many others that fill the universe.*

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*Giordano Bruno (1548–1600), an Italian philosopher, postulated that the sun was but one star among many and that around these other stars were planets. This, and other scientific heresy, got him burned alive in Rome.

The first extrasolar planets, or exoplanets, discovered were found in extremely inhospitable locations orbiting pulsars. Pulsars are rapidly rotating neutron stars that emit regular pulses of radiation, including radio waves, gamma rays, and x-rays, at rates of about one thousand pulses per second. A pulsar's pulse rate is regular and predictable, so much so that they are being considered for use in celestial navigation (see chapter 7, "Designing Interstellar Starships"). Tiny variations in the pulses led to the inference that the observed irregularity was caused by orbiting planets, and *voilà*, the first (indirect) evidence of exoplanets.[1] Optical observers caught up to the accuracy needed for similar feats, and shortly thereafter astronomers were also detecting extrasolar planets around mostly sunlike stars via the Doppler shifts produced by the planets' perturbations of the stars.* Basically, just as a star's gravity tugs on the planets circling it to keep them in orbit, so do the masses of the planets pull on the star. Given the mass differences, the gravitational pull on the star is extremely small compared with the reverse, but it is not zero. Therefore, as a planet orbits a star, the planet will pull on it, causing the star to move slightly toward the planet, inducing it to wobble. Since the star is constantly emitting light, the wobble can be detected as a small Doppler shift in the light's wavelength. These measurements by themselves gave only lower limits to the planets' masses but were an important clue to the abundance of (Jupiter-mass) planets.

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*Light emitted or reflected from objects moving away from the observer is stretched out to slightly longer wavelengths due to the object's motion. Light emitted or reflected from an object moving toward the observer is analogously compressed to shorter wavelengths. The amount of elongation or compression depends on the object's speed. This is called a Doppler shift, and it is the reason the radar guns used by police can so quickly determine if you are speeding while driving.

In about 2000, astronomers began finding exoplanets using the transit method. The best way to understand how this works is to think about a solar eclipse. When the moon passes between Earth and the sun along the line of sight, the moon casts a shadow on Earth that you can see. Now imagine looking into our solar system from outside the orbit of Pluto with one of the eight planets crossing your field of view as you stare at the sun. With sensitive instruments, you would see the light from the sun dim slightly as the planet passes between your instrument and the sun, blocking some of the light. If you hold your position long enough, let's say several Earth years, then you could theoretically see the same planet complete multiple orbits around the sun, causing a dimming that regularly repeats. If you were to change your viewing direction to look at a star other than the sun and have even more sensitive instruments, then you would see the dimming of that star caused by any planets that orbit it along your line of sight—the transit method. Of course, given the distances and the relative sizes of planets as compared to the stars they are transiting, the instruments needed to see the dimmed light must be quite sensitive, and the data-processing software required is complex. The analogy I like to use is that of trying to determine the size of a mosquito (the planet) flying in front of your car's headlights (the star) while you stare at it on a dark night.

There are many other methods now used to find and characterize exoplanets, and multiple space missions have flown for just that purpose. As a result, and according to NASA's Exoplanet Exploration website, there are now more than four thousand confirmed exoplanets, and more than five thousand additional potential exoplanets awaiting independent confirmation.[2]

And now the story gets even more interesting. Among these exoplanets, there are several that are near Earth size and orbiting their parent stars in that star's habitable zone. This means that not only is the planet similar in size to Earth (some larger, like Neptune; some smaller, like Mars), but it is in a region around the star where the temperature is not too hot, nor too cold, for liquid water and the chemistry essential for life as we know it to exist. Scientists have identified about sixty such potentially habitable planets.[3] Given that we have only been able to search among the stars nearest to Earth, and there are about 100 billion stars in the Milky Way alone, using these statistics, the current best estimate for the number of near-Earth-size planets in habitable zones around other stars is . . . drumroll . . . between 11 billion and 40 billion.[4]

Wow. That is a lot of potential real estate waiting to be discovered, mapped, and explored. How soon can we go?

The answer to this question is not something to which a specific date or range of dates can be assigned. At least, not yet. To answer it, we need first to understand how far away these exoplanets are and more about what lies between us and them. Let's start by thinking about the vastness of space and our notions of infinity.

If you want to touch the infinite,* go outside on a cloudless night and look at the stars. You will have to put down your phone, e-book reader, or other gadget and find a spot away from bright lights so your eyes can get adjusted to the darkness. (All right, this will be a challenge for city dwellers, but that is not an excuse.) Once you are there, look up and find as many pinpoints of light in the sky as you can. A few of the lights you see will be planets in our solar system, like Mars or Jupiter, reflecting light from the sun. Others will be stars or collections of stars

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*Okay, the universe is not really infinite. But for all practical purposes (note I say "practical"), it is as close to the infinite as we will likely ever see or know.

that, like the sun, emit their own light. Stand or sit quietly and think about the light you see. The particles of light, called photons, that impinge on your eyes have been traveling through space a long time, hundreds, thousands, and perhaps millions of years, and they end their journey through deep space when they reach your eyes and touch *you*.

In the vacuum of space, light travels at about 186,000 miles per *second* (300,000 kilometers per second). On a sunny day, the light that illuminates the world around us traveled through space for about eight minutes, at a speed of 186,000 miles per second, from the time it left the sun until it touched your skin and began giving you a sunburn. Eight minutes. Since you are now outside looking at the night sky, consider the light reflecting from Jupiter, the largest planet in the solar system. Jupiter is typically one of the brightest objects in the night sky because it is so large (eleven Earths can line up across its equator) and therefore reflects a lot of light. At its closest, Jupiter is just over 365 million miles from Earth, and the light you see reflecting from it took about forty-one minutes to get from the sun to the planet and nearly thirty-three minutes to travel from the planet to your eyes—for a total of about seventy-four minutes! The most distant planet, Neptune, is so far away that it takes the light reflecting from it about four hours to touch your eyes. Compared to the stars, these distances to the planets are small.

If you live in a big city, that might be all you can see—even on a clear night. The combination of streetlights, automobiles, and light leaking from the apartments and homes around you, combined with the humidity of the air, might make it nearly impossible to see what those blessed with dark skies can see from more rural areas. Away from the lights of civilization, the average person can see about two thousand stars in the sky. Among the closest, easily visible to those living in the southern hemisphere, are Alpha Centauri A and B. The light they emit travels through space for more than four years to reach Earth and touch your eyes. Four years! And these stars are relatively close to us. To make discussion of these immense distances easier, astronomers call the distance light travels in a year a light-year. On this scale, Alpha Centauri A and B are 4.35 light-years (LY) away.

If we were limited to seeing the stars using only our eyes, then we would be seeing objects that are many times more distant than Alpha Centauri A and B, but we would be missing the bigger picture—the much bigger picture—that is the universe in which we live. Early telescopes allowed people to look at the reflected light from the planets and see that they were big, round objects like Earth, orbiting the sun at ever greater distances. They also allowed people to see many more stars than are visible to the naked eye, including some fuzzy, spiral-shaped objects, generically called "nebulae," which were so lovingly and systematically categorized by Charles Messier (and are now known as Messier Objects).[5] Until Edwin Hubble came along, astronomers considered what we now know as galaxies to be some of these "nebulae." Exploded stars within our own galaxy were also "nebulae." In fact, given the limitations of those early telescopes, just about anything that looked like a fuzzy cloud of dust or gas was labeled a "nebula." Nebulae were everywhere, and there wasn't much to distinguish between the various types.

In the early 1920s, while using the 100-inch mirror at the Mount Wilson observatory, Hubble took the highest-resolution images to date of the Andromeda Nebula and discovered that it was actually an extremely distant clumping of many stars, like our Milky Way Galaxy.[6] A few years later, he calculated that this new galaxy must be at least ten times more distant than the most distant stars within our Milky Way. Telescopes improved and many more nebulae were found to be, in fact, distant galaxies. Thanks to modern telescopes, including one named after Edwin Hubble flying in space over 300 miles above in Earth orbit, we now know that there are billions of galaxies in the universe, each containing billions of stars—and we can "see" many of them, thanks to our telescopes here on the ground and in space.

We now know that the multibillion-star cluster that is our own galaxy, the Milky Way, is about 100,000 light-years across. In other words, it takes light about 100,000 years to travel from one side of the Milky Way to the other. One of the nearest galaxies to ours, Andromeda, is nearly 2.5 *million* LY away. If you are stargazing on a clear, dry night, far from city lights, then one of the tiny "stars" you can see is not a star at all—it is the Andromeda Galaxy. Keeping in the theme of touching eternity, consider that the light from Andromeda that touches your eye (touches *you*!) traveled through space more than 2 million years. When you see it, you are truly touching the nearly infinite.

If Alpha Centauri A and B are the nearest stars, and Andromeda is one of the nearest galaxies, what about the farthest? Similar to how our eyes are limited to seeing only about two thousand stars, and the early telescopes were limited to seeing mostly the planets and a few more stars, our current telescopes are limited by current technological abilities. Seen by the Hubble Space Telescope in 2015, EGS8p7 is one of the most distant galaxies ever observed at 13.2 billion light-years.[7]

If you are like me and, I suspect, most people (some astronomers excluded, maybe), then the differences in these distances are almost meaningless and completely outside your everyday experience. How can anyone comprehend the difference between the distance to the sun (at eight light-minutes) and the distance to Neptune (four light-hours) with the distance to Alpha Centauri A and B, let alone Andromeda? For fun, let's try.

First, let's invent our own measuring stick. We start with a scale developed by astronomers, the astronomical unit (AU), which is the sun-to-earth distance of 93 million miles. Using this scale, Earth is 1 AU from the sun. Let's visualize this by creating a scale model of the solar system that will fit into a typical classroom, with 1 AU corresponding to 1 foot (~30 cm) and use this distance to build a mental model of the solar system and beyond.* Earth is 1 AU, 1 foot, from the sun; therefore, on this scale, Mars is ½ foot (AU) away, and Neptune 30 feet (AU). Note that we regularly launch rockets to Mars, and it takes them approximately seven months to cover the Earth-to-Mars distance of ½ foot. Voyager took about twelve years to reach Neptune. On this scale, the nearest stars (Alpha Centauri A and B), would be 268,770 feet, or about 51 miles (~82 km) away. And those are the nearest stars! The best attempt at visualizing the distances involved on a single image can be seen in figure 1.1. Significant solar system objects are specifically labeled, as are the approximate locations of the Voyager spacecraft and the stars in the Centauri system. The part that is a bit difficult to understand, and is also the only way the vast distances involved can be compressed and viewable on the graphic, is the horizontal axis—each distance increment on the axis is ten times farther than the previous one.

I will leave it to you to figure out how far away the Andromeda Galaxy lies on this scale . . . The bottom line: space is big.

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*I chose to use the imperial measurement system because my shoe size measures almost exactly 1 foot, which is very convenient. I have walked out this solar system scaling in many classrooms and lecture halls.

Really big. *Unimaginably* big. How, then, can we ever hope to bridge the gap and visit planets circling other stars?

Again, by thinking big, as I will explain. Interstellar travel is not for the timid. We need to consider that there is more than just the distance when we contemplate traveling across the void to visit a planet circling another star. Contrary to what you may think, space is not just a vacuum with a few planets and stars dropped here and there. We need to consider what else lies between us and where we want to go before we can even begin seriously thinking of going there.

First, space is not empty, just *almost* empty. In our solar system, the sun sits at the center and serves as not only the source of heat and light that gives the solar system life, but also as the gravitational anchor around which the eight planets, five known dwarf planets (Pluto is considered a dwarf planet, as are Ceres, Haumea, Makemake, and Eris), as well as hundreds of thousands of asteroids and comets orbit. The sun is, by far, the largest object in the solar system, with a diameter across which you could place more than 109 Earths side to side and more than 1 million Earths in its volume. Almost all of the mass in the solar system—99.8 percent—is in the sun. Jupiter, the largest planet, could contain only a paltry 1,300 Earths in its volume. Of the remaining planets, some are larger than Earth, some smaller. When you combine the masses of all the planets, dwarf planets, asteroids, and comets, you would have most, but not all, of the remaining 0.2 percent of the solar system's mass.

It is this small fraction of a percent that might cause problems for interstellar spacecraft as they exit the solar system and enter another one—and perhaps, to a lesser extent, in the void between the stars. Left over from when the solar system was formed—and created when asteroids, comets, and planets collide (or have collided, many years in the past)—are meteoroids

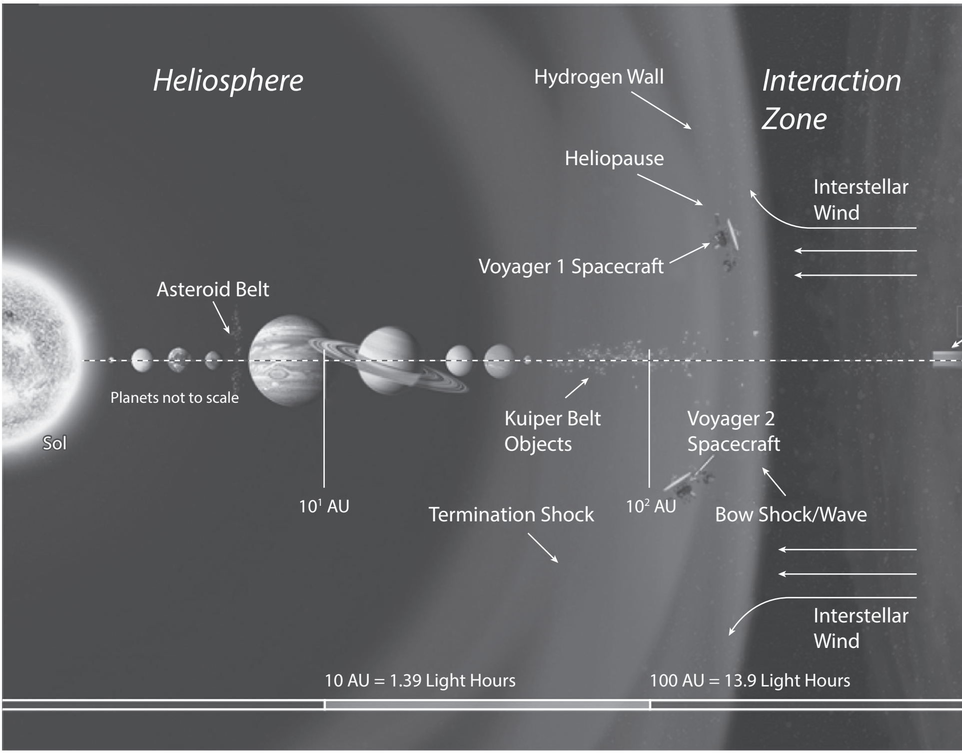

FIGURE 1.1. Interstellar Distances Scale. The distance to the nearest star is extremely difficult to capture in one image, and thankfully the folks at the Keck Institute for Space Studies did it for us in a creative way. Going left to right, the distances from the Sun to various objects are shown in six equal-size increments, with each one shortening the apparent distance by a factor of ten in what is called a logarithmic scale. In other words, the objects in the second increment are ten times farther away than those in the first. Those in the third increment are ten times farther away than those in the second and one hundred times farther away than those in the first. This 10× scaling continues until we reach Alpha Centauri, with the last increment representing distances that are up to one hundred thousand (100,000) times farther away than those in the first increment. Keck Institute for Space Studies / Chuck Carter.

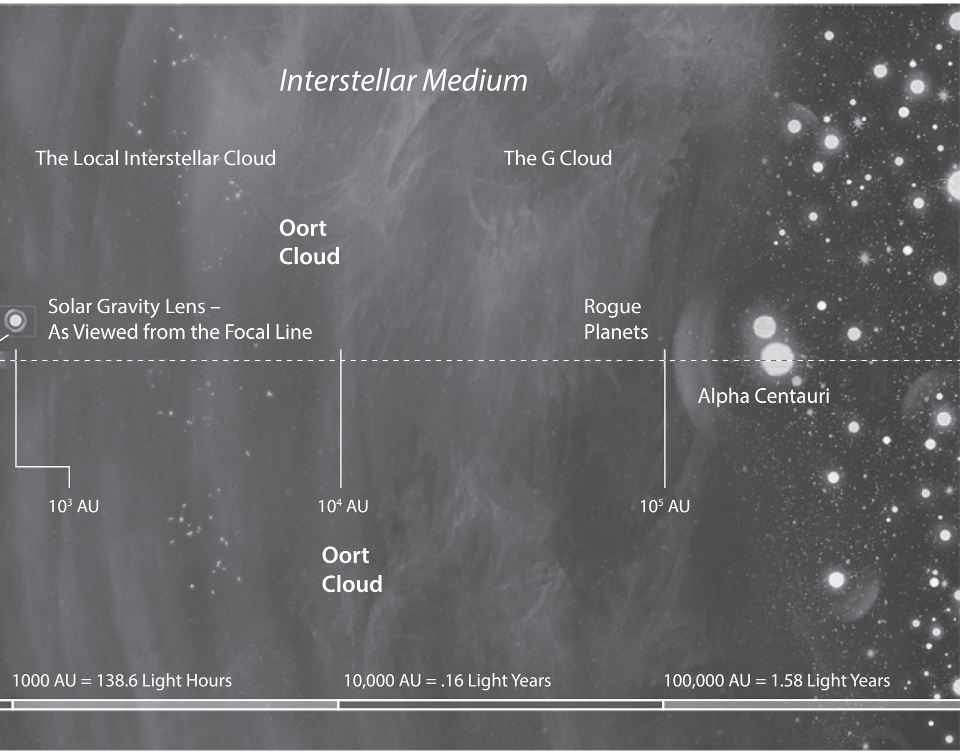

FIGURE 1.1. (*continued*)

and dust. Zipping along at faster than 20 km/sec (~12 miles per second), some as fast as 50 km/sec, these small pieces of rock and dust crisscross the solar system and pose a potential risk to existing spacecraft and those we might send outward to the stars in the future. Small meteoroids weigh between 10^{-9} and 10^{-2} g and carry a lot of kinetic energy due to their extremely fast velocity. For example, a meteoroid weighing the same as a piece of sand, 0.011 g, traveling at 20 km/sec has a kinetic energy of 2,200 joules, which is about thirteen times more than a 0.22-caliber rifle bullet due to its much faster speed. A bullet or meteoroid does damage when it hits something because its energy of motion—the kinetic energy mentioned above—is converted into heat at the point of impact and along its path as it penetrates the material.

Have you seen a shooting star? These stars are small pieces of debris that enter Earth's atmosphere at high speed and burn up as they slow down and lose their kinetic energy of motion by heating the atmosphere through which they are traveling, causing it to glow and creating the light trail we observe. Believe it or not, Earth gains 20,000 to 40,000 tons of weight each year due to infalling dust and meteors (meteoroids are called meteors when they enter the atmosphere).[8]

And yet we still consider space to be mostly empty. Considering that we humans are extremely small when compared to the size of Earth, and Earth is extremely small when compared to the sizes of the sun and Jupiter, and then add in the tons of dust and debris that Earth accumulates each year, one might think that the solar system is filled with a lot of mass. It is not. Though not empty, it is filled with meteoroids and dust zipping hither and yon, sometimes falling to Earth and sometimes hitting our spacecraft, causing varying amounts of damage—from minor pitting of the surface to a mission-ending collision. Potential impacts with natural space objects must be accounted for as we plan our trip to the stars.

Fortunately, the locations of all the large space objects (planets, dwarf planets, asteroids, and comets) are fairly well known, and when compared to the volume of the solar system, the probability of running into one as you cross the solar system traveling at any speed is extremely low. Not so, however, with the dust and meteoroids. While they are small and widely separated, they are there and will continue to pose a risk to spacecraft. The good news is that the likelihood for one of our spacecraft, even larger ones, hitting a piece of debris that causes significant damage is ridiculously small and has only happened once, with Mariner 4.[9] Note, however, that the probability of such an impact is a function of distance traveled. And, as noted above, the distances we have so far sent our spacecraft are extremely small when compared to the distances they will traverse in going to another star. Even low-probability events are likely to happen given enough time, and the likelihood of hitting something significant during a light-years-long voyage is high.

And we aren't through discussing what is in the "vacuum" of space yet.

In addition to gravity and light, the sun is pumping tons of hydrogen and helium across the solar system at speeds between about 185 and 500 miles per second in something called the solar wind.[10] If the solar wind radiation reached Earth's surface, it would severely damage the biosphere and life within it. Earth's magnetic field serves as a shield, redirecting the material around the planet so that it streams beyond it. The force of the solar wind changes Earth's magnetic field so that it is compressed inward on the sun-facing side and stretched out on the night side. These fast-moving particles also cause damage to electronics and can completely disable spacecraft over time or quickly, especially during a solar storm (a period of increased radiation emissions from the sun—in other words, when the sun burps and spits out higher-energy, higher-density radiation in clouds larger than Earth that then move outward from the sun and could impact our planet, our spacecraft, or both). Space mission planners design spacecraft electronics to be radiation resistant, but it is not possible to make them immune to the radiation's effects. Given enough time, most spacecraft electronics exposed to solar radiation will fail.

The solar system and interstellar space are filled with magnetic fields. As known physical processes allow Earth's molten iron core to generate a magnetic field for our compasses to use in pinpointing north, so too do they allow the sun to create an enormous magnetic field that extends far out into space, encircling all the planets in the solar system and beyond. The combined interaction of the solar magnetic field and the solar wind define the heliosphere, the edge of which is called the heliopause (where the sun's outward flowing radiation pressure is balanced by the inward-coming radiation pressure flowing across deep space from all the other stars in the Milky Way). The heliopause is considered by many (but not all!) to define the boundary between the solar system and interstellar space.[11]

These interstellar magnetic fields play a role in the development of another component of the interstellar medium: galactic cosmic rays (GCRs), highly energetic charged particles that permeate space. GCRs were most likely formed when stars elsewhere in the galaxy exploded and sent huge clouds of highly energetic and ionized atoms out into space where they were further accelerated by the interstellar magnetic field to even higher energies. There are not many of them, but over time they can destroy electronics and damage biological life. (GCRs and their impact on interstellar starships will be discussed further in chapter 7.)

And then there is interstellar hydrogen. The heliopause, described above, is where the outward pressure of solar radiation, which is mostly hydrogen, is roughly equal to the inward pressure of the radiation from all the other stars in the Milky Way. This means that the interstellar space surrounding the solar system is filled with hydrogen emitted long ago from other stars and celestial objects. The density is low, with interstellar space averaging about one hydrogen atom per cubic centimeter.[12] If you are traveling very rapidly, these hydrogen atoms become nearly indistinguishable from the high-energy protons flowing outward from the sun; there is no difference between a slow-moving spacecraft being bombarded by fast-moving hydrogen atoms (as from the sun) and a fast-moving spacecraft plowing through slow-moving hydrogen atoms. This diffuse cloud of atoms might just play a role in the viability of at least one advanced propulsion system that will be discussed in later chapters.

Now that we better understand what's out there, there are many questions that need to be answered. Among them are:

- How will we learn which extrasolar planets we should visit? Which might be like Earth?
- Knowing the vast distances involved and given our current understanding of physics and how nature works, how will we get there from here?
- We understand well the environment of deep space in our own solar system; what about when we cross the heliopause and begin our long journey through interstellar space?
- When and how can we make the trip?

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