TWENTY-THREE

GOLDILOCKS AND THE THREE PLANETS

Once upon a time, some four billion years ago, the formation of the solar system was nearly complete. Venus had formed close enough to the Sun for the intense solar energy to vaporize what might have been its water supply. Mars formed far enough away for its water supply to be forever frozen. And there was only one planet, Earth, whose distance was "just right" for water to remain a liquid and whose surface would become a haven for life. This region around the Sun came to be known as the habitable zone.

Goldilocks (of fairy-tale fame) liked things "just right," too. One of the bowls of porridge in the Three Bears' cottage was too hot. Another was too cold. The third was just right, so she ate it. Also in the Three Bears's cottage, one bed was too hard. Another was too soft. The third was just right, so Goldilocks slept in it. When the Three Bears came home, they discovered not only missing porridge but also Goldilocks fast asleep in a bed. (I forget how the story ends, but if I were the Three Bears—omnivorous and at the top of the food chain—I would have eaten Goldilocks.)

The relative habitability of Venus, Earth, and Mars would intrigue Goldilocks, but the actual story of these planets is somewhat more complicated than three bowls of porridge. Four billion years ago leftover water-rich comets and mineral-rich asteroids were still pelting the planetary surfaces, although at a much slower rate than before. During this game of cosmic billiards, some planets had migrated inward from where they had formed while others were kicked up to larger orbits. And among the dozens of planets that had formed, some were on unstable orbits and crashed into the Sun or Jupiter. Others were ejected from the solar system altogether. In the end, the few that remained had orbits that were "just right" to survive billions of years.

Earth settled into an orbit with an average distance of 93 million miles from the Sun. At this distance, Earth intersects a measly one two-billionth of the total energy radiated by the Sun. If you assume that Earth absorbs all incident energy from the Sun, then our home planet's average is about 280 degrees Kelvin (50 degrees F), which falls midway between winter and summer temperatures. At normal atmospheric pressures, water freezes at 273 degrees and boils at 373 degrees Kelvin, so we are well-positioned for nearly all of Earth's water to remain in a happy liquid state.

Not so fast. Sometimes in science you can get the right answer for the wrong reasons. Earth actually absorbs only two-thirds of the energy that reaches it from the Sun. The rest is reflected back into space by Earth's surface (especially the oceans) and by the clouds. If reflectivity is factored into the equations, then the average temperature for Earth drops to about 255 degrees Kelvin, which is well below the freezing point of water. Something must be operating in modern times to raise our average temperature back to something a little more comfortable.

But wait once more. All theories of stellar evolution tell us that 4 billion years ago, when life was forming out of Earth's proverbial primordial soup, the Sun was a third less luminous than it is today, which would have placed Earth's average temperature even further below freezing.

Perhaps Earth in the distant past was simply closer to the Sun. But after the early period of heavy bombardment, no known mechanisms could have shifted stable orbits back and forth within the solar system. Perhaps the greenhouse effect was stronger in the past. We don't know for sure. What we do know is that habitable zones,

as originally conceived, have only peripheral relevance to whether there may be life on a planet within them.

The famous Drake equation, invoked in the search for extraterrestrial intelligence, provides a simple estimate for the number of civilizations one might expect to find in the Milky Way galaxy. When the equation was conceived in the 1960s by the American astronomer Frank Drake, the concept of a habitable zone did not extend beyond the idea that there would be some planets at the "just right" distance from their host stars. A version of the Drake equation reads: Start with the number of stars in the galaxy (hundreds of billions). Multiply this large number by the fraction of stars with planets. Multiply what remains by the fraction of planets in the habitable zone. Multiply what remains by the fraction of those planets that evolved life. Multiply what remains by the fraction that have evolved intelligent life. Multiply what remains by the fraction that might have developed a technology with which to communicate across interstellar space. Finally, when you introduce a star formation rate and the expected lifetime of a technologically viable civilization you get the number of advanced civilizations that are out there now, possibly waiting for our phone call.

Small, cool, low-luminosity stars live for hundreds of billions and even possibly trillions of years, which ought to allow plenty of time for the planets around them to evolve a life-form or two, but their habitable zones fall very close to the host star. A planet that forms there will swiftly become tidally locked and always show the same face toward the star (just as the Moon always shows the same face to Earth) creating an extreme imbalance in planetary heating—all water on the planet's "near" side would evaporate while all water on the planet's "far" side would freeze. If Goldilocks lived there, we would find her eating oatmeal while turning in circles (like a rotisserie chicken) right on the border between eternal sunlight and eternal darkness. Another problem with the habitable zones around these long-lived stars is that they are extremely narrow; a planet in a random orbit is unlikely to find itself at a distance that is "just right."

Conversely, large, hot, luminous stars have enormous habitable zones in which to find their planets. Unfortunately these stars are rare, and live for only a few million years before they violently explode, so their planets make poor candidates in the search for life as we know it—unless, of course, some rapid evolution occurred. But animals that can do advanced calculus were probably not the first things to slither out of the primordial slime.

We might think of the Drake equation as Goldilocks mathematics—a method for exploring the chances of getting things just right. But the Drake equation as originally conceived misses Mars, which lies well beyond the habitable zone of the Sun. Mars displays countless meandering dry riverbeds, deltas, and floodplains, which constitute in-your-face evidence for running water in the Martian past.

How about Venus, Earth's "sister" planet? It falls smack dab within the Sun's habitable zone. Covered completely by a thick canopy of clouds, the planet has the highest reflectivity of any planet in the solar system. There is no obvious reason why Venus could not have been a comfortable place. But it happens to suffer from a monstrous greenhouse effect. Venus's thick atmosphere of carbon dioxide traps nearly 100 percent of the small quantities of radiation that reach its surface. At 750 degrees Kelvin (900°F) Venus is the hottest planet in the solar system, yet it orbits at nearly twice Mercury's distance from the Sun.

If Earth has sustained the continuous evolution of life through billions of years of storm and drama, then perhaps life itself provides a feedback mechanism that maintains liquid water. This notion was advanced by the biologists James Lovelock and Lynn Margulis in the 1970s and is referred to as the Gaia hypothesis. This influential, yet controversial idea requires that the mixture of species on Earth at any moment acts as a collective organism that continuously (yet unwittingly) tunes Earth's atmospheric composition and climate to promote the presence of life—and by implication, the presence of liquid water. I am intrigued by the idea. It has even become the darling of the New Age movement. But I'd bet

there are some dead Martians and Venusians who advanced the same theory about their own planets a billion years ago.

THE CONCEPT OF a habitable zone, when broadened, simply requires an energy source of any variety to liquefy water. One of Jupiter's moons, icy Europa, is heated by the tidal forces of Jupiter's gravitational field. Like a racquetball that heats up after the continuous stress of getting hit, Europa is heated from the varying stress induced by Jupiter pulling more strongly on one side of the moon compared with the other. The consequence? Current observational and theoretical evidence suggest that below the kilometer-thick surface ice there is an ocean of liquid water, possibly slush. Given the fecundity of life within Earth's oceans, Europa remains the most tantalizing place in the solar system for the possibility of life outside Earth.

Another recent breakthrough in our concept of a habitable zone are the newly classified extremophiles, which are life-forms that not only exist but thrive in climactic extremes of hot and cold. If there were biologists among the extremophiles, they would surely classify themselves as normal and any life that thrived in room temperature as an extremophile. Among the extremophiles are the heat-loving thermophiles, commonly found at the midocean ridges, where pressurized water, superheated to well beyond its normal boiling point, spews out from below Earth's crust into the cold ocean basin. The conditions are not unlike those within a household pressure cooker, where high pressures are supplied by a heavy-duty pot with a lockable lid and the water is heated beyond ordinary boiling temperatures, without actually coming to a boil.

On the cold ocean floor, dissolved minerals instantly precipitate out from the hot water vents and form giant porous chimneys up to a dozen stories tall that are hot in their cores and cooler on their edges, where they make direct contact with the ocean water. Across this temperature gradient live countless life-forms that have never seen the Sun and couldn't care less if it were there. These hardy bugs live on geothermal energy, which is a combination of the leftover heat from Earth's formation and heat continuously leaching into Earth's crust from the radioactive decay of naturally occurring yet unstable isotopes of familiar chemical elements such as Aluminum-26, which lasts millions of years, and Potassium-40, which lasts billions.

At the ocean floor we have what may be the most stable ecosystem on Earth. What if a jumbo asteroid slammed into Earth and rendered all surface life extinct? The oceanic thermophiles would surely continue undaunted in their happy ways. They might even evolve to repopulate Earth's surface after each extinction episode. And what if the Sun were mysteriously plucked from the center of the solar system and Earth spun out of orbit, adrift in space? This event would surely not merit attention in the thermophile press. But in 5 billion years, the Sun will become a red giant as it expands to fill the inner solar system. Meanwhile, Earth's oceans will boil away and Earth, itself, will vaporize. Now that would be news.

If thermophiles are ubiquitous on Earth, we are led to a profound question: Could there be life deep within all those rogue planets that were ejected from the solar system during its formation? These "geo"thermal reservoirs can last billions of years. How about the countless planets that were forcibly ejected by every other solar system that ever formed? Could interstellar space be teeming with life formed and evolved deep within these homeless planets? Far from being a tidy region around a star, receiving just the right amount of sunlight, the habitable zone is indeed everywhere. So the Three Bears's cottage was, perhaps, not a special place among fairy tales. Anybody's residence, even that of the Three Little Pigs, might contain a sitting bowl of food at a temperature that is just right. We have learned that the corresponding fraction in the Drake equation, the one that accounts for the existence of a planet within a habitable zone, may be as large as 100 percent.

What a hopeful fairy tale this is. Life, far from being rare and precious, may be as common as planets themselves.

And the thermophilic bacteria lived happily ever after—about 5 billion years.