Science Fact

The Science Behind *Kepler's Laws*

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Life evolves to fit its environment, whether that's a frozen tundra or a steamy rainforest. On Kepler, that means life had to adapt to a hypoxic atmosphere, a deficiency of nitrogen, and low-energy solar radiation that is diminished in brightness by high-altitude methane clouds. Those factors alone led life down a very different path from the one taken by life on Earth.

But another factor also drives evolution, one that is potentially more important but is often overlooked—the chemical nature of the molecules of heredity. It's understandable that this factor is rarely considered; virtually all life on Earth uses DNA to store genetic information. Life on Kepler never made the transition from RNA to DNA, and the long-term consequences of that quirk proved to be deadly to the colonists on the planet.

In this essay, we'll examine the physical and biochemical conditions that drove the evolution of life on Kepler.

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There's Something in the Air

Let's start with the planet itself. Kepler orbits a K-type star; that is, a star that is a bit cooler and dimmer than Earth's Sun. The name Kepler originally belonged to the star, its catalogue number long forgotten[1], but the colonists there quickly adapted the name to the planet itself. The planet's orbit is more elliptical than any planet in Earth's Solar System. Its axial tilt is close to zero, so its seasons are driven more by the insolation differences between perihelion and aphelion.[2] In the temperate zones, the weather is generally warm and dry around perihelion. As the planet approaches aphelion, temperatures cool and dissolved water condenses out of the atmosphere, leading to a rainy season.

Kepler retains a thicker atmosphere than Earth due to its greater mass and the lower amount of high-energy radiation emitted by its sun. The atmosphere's composition (**see table 1**) is an

Table 1: Kepler's Atmosphere

Gas	Partial Pressure (in atmospheres)	
	Kepler	Earth
Methane	0.84 atm	2×10^{-6} atm
Nitrogen	0.49 arm	0.78 atm
Oxygen	0.07 atm	0.21 atm
Carbon Dioxide	5×10^{-5} atm	4×10^{-5} atm
Other gases	<0.01 atm	<0.01 atm
TOTAL PRESSURE	1.41 atm	1.00 atm

important driver of the evolution of life on the surface. Much of the atmosphere's methane and oxygen is likely biogenic, but the anomalously low concentration of nitrogen hints at an atmospheric history much different from Earth's.

Like Earth, Kepler probably gained its early atmosphere by volcanic outgassing of ammonia, carbon dioxide, and water vapor. On Earth, the water vapor condensed into oceans while the ammonia decomposed to produce nitrogen gas. Much of Kepler's early atmosphere must have been stripped away at some point after the water condensed out, leaving the atmosphere deficient in nitrogen. One model suggests that Kepler's orbit was originally closer to its sun and the atmosphere was lost due to solar wind ablation. Later, the orbit migration of an outer gas giant stretched Kepler's orbit into its current more distant and elliptical orbit. A competing theory proposes that Kepler's sun went through a stage where it produced intense flares that stripped away much of the planet's early atmosphere. The atmosphere was later enriched with water, methane, and carbon dioxide by cometary impacts.

Life on Kepler first evolved in the planet's shallow oceans. As on Earth, early cells were primarily methanogenic, relying on the reaction

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$$

to produce energy. Eventually, the evolution of photosynthesis provided a second pathway of energy production. Since Kepler's sun produces comparatively few high-energy photons, photosynthesis never became dominant enough to supplant methanogenesis. The photosynthetic production of sugars like glucose did, however, allow for the evolution of a new form of methanogenesis. Cells degrade glucose[3] to produce acetic acid (CH_3COOH), then convert this molecule to methane by the reaction

$$CH_3COOH \rightarrow CH_4 + CO_2$$

The oxygen in Kepler's atmosphere is a result of photosynthesis, as it is on Earth. As oxygen concentrations rose, life developed additional energy-production pathways using the gas. Multiple such oxidative pathways exist, but none are as efficient or as dominant as the citric acid cycle[4] in Earth life.

Modern life on Kepler uses this combination of photosynthesis, glycolysis, methanogenesis, and acetate oxidation as its primary metabolic pathways. The thermodynamics of this metabolism is not thoroughly understood and further study is recommended.[5] As on Earth, these life processes have a profound effect on the composition of Kepler's atmosphere. The production and use of methane, carbon dioxide, and oxygen by the planet's living organisms leads to the equilibrium gas concentrations we see in the atmosphere today.

* * *

It's Alive

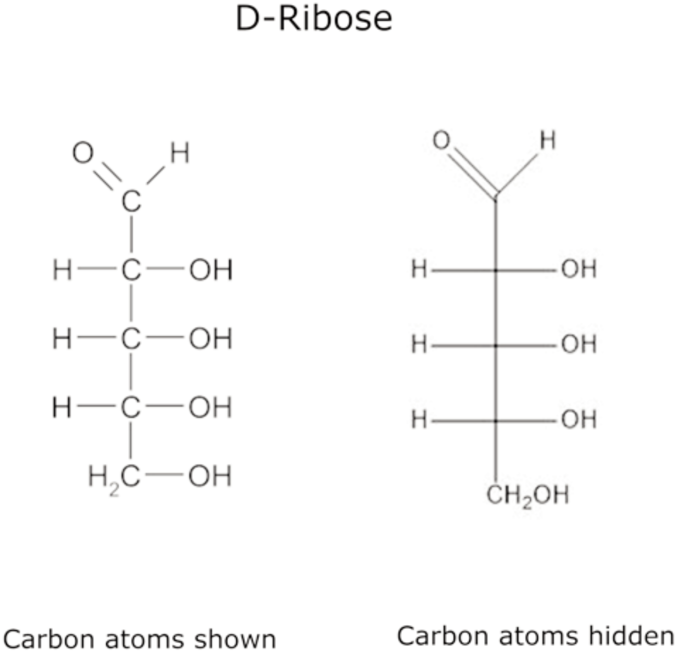
The biochemical basis of life on Kepler is wildly different from Earth's life in some ways and intriguingly similar in others. The overall building blocks are the same—proteins, ribose-based nucleic acids, lipids, and sugars. Two important differences lead to the vastly different evolutionary paths seen on the two worlds—protein deficiency and an alternative form of ribose.

The protein deficiency is a consequence of the low concentration of nitrogen in Kepler's atmosphere. Proteins are made from amino acids, which require nitrogen. Earth organisms "fix" nitrogen from the air by reducing it to ammonia, which can then be incorporated into amino acids. On Kepler, the nitrogen is fixed by direct combination with organic chains to produce imines, which are then reduced to amines[6], but the result is the same.

Both proteins and nucleic acids require nitrogen and, since Kepler has less available, life evolving there needed to use these compounds judiciously. While Earth life often uses proteins for structure and support, Kepler's life replaces these with polysaccharides like cellulose and chitin. In some cases, these saccharide chains are supplemented with occasional amino acid side groups that allow for protein-like cross linkages that improve strength and elasticity. Another important role proteins fill is that of biological catalysts, or enzymes. On Kepler, RNA strands take over this function.

Before we can understand how that works, we're going to have to take a close look at the sug-

Figure 1: The Structure of Ribose



The carbon chain structure of the sugar ribose. Chemists often omit the carbon atoms in large molecules for clarity. Each point where lines (bonds) cross is assumed to be a carbon atom.

Attributions:
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Structure on the right:
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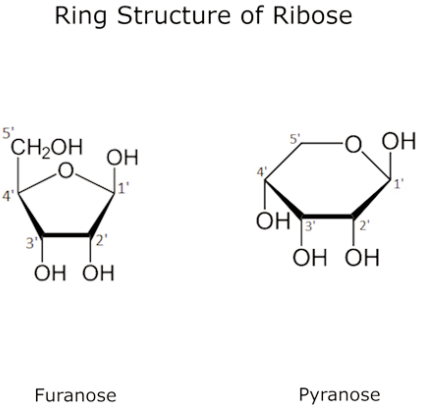
Figure 2: Furanosyl and Pyranosyl Forms of Ribose



Carbon atoms are numbered for reference. The major difference between the two forms is that carbon 5' hangs off the end of the ring in the furanose form, while in the pyranose form carbon 5' is incorporated into the ring. The change in ring structure has subtle effects on the folding and coiling of the RNA molecule built from the ribose units.

ar at the heart of RNA, ribose. Ribose is a five-carbon sugar whose structure is shown in **figure 1**. In addition to the chain form shown, sugars can also exist in ring forms.[7] The ring-forming reaction can occur between the first and fourth carbon atoms, producing a five-member ring called a furanose, or between the first and fifth carbons, making a six-member ring called a pyranose (see **figure 2**).

Life on Earth uses the furanosyl form of ribose to make RNA. Some have suggested that the earliest life forms actually used pyranosyl RNA (pRNA) and later switched over to modern furanosyl form, and the discovery of life on Kepler lends credence to this theory. In ancient life, RNA filled two major roles—encoding genetic information and acting as a catalyst. RNA strands that act as catalysts are called ribozymes, short for ribonucleic acid enzymes. Eventually, proteins took over the enzyme role[9], and DNA took over the coding function.

Kepler's life never made the switch from pRNA. Biologists are uncertain why the change occurred on one planet and not the other. Some contend that the changeover on Earth was mere happenstance, a lucky mutation. Others believe that the deficiency of nitrogen in Kepler's atmosphere made proteins a less attractive option and so the existing pRNA was never freed of its ribozyme function, locking it into the existing pyranosyl form. As a consequence, Kepler's life never made the jump to DNA. The reliance on pRNA as a carrier of the genetic code drove evolution on Kepler in a very odd direction.

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Swapping Genes

DNA is more stable than RNA, enabling it to form very long strands. Strands have a tendency to pair up and twist into a double helix. The double helix allows for error correction; if one strand is damaged, the other can be used as a template to repair it. This behavior drove Earth life to put all its genetic eggs into one nucleic basket. An organism's genes are stored on a small number of large DNA molecules. It wasn't long before living organisms began to sequester these critical molecules into a specialized nucleus, and eukaryotic life was born.

RNA, on the other hand, forms relatively short chains, and those chains tend to fold back on themselves rather than pairing up. The pRNA-based life on Kepler never had the opportunity to develop a centralized molecule to store its genetic data, and therefore had no need to evolve a nucleus. Instead, genetic information is dispersed on small pRNA strands distributed throughout the cytoplasm.

With decentralization comes flexibility. Cells can specialize or generalize as much as needed, on the fly, by picking up or discarding pRNA sequences. When behaving as a unicellular organism, a cell retains the genes needed for metabolism and other fundamental cellular functions. Even then there is room for variation; soil cells near the surface will retain the genes for structures like chlorophyll that allow photosynthesis while cells buried deep in the soil will shed those genes and opt for genes that facilitate life as a decomposer.

The ability to shed genes is facilitated by transfer proteins embedded in the cell membrane. What's more, these proteins can work both ways, allowing for the import of pRNA strands as well. Thus, nearby cells can share genes with each other by passing pRNA sequences back and forth through their membranes. This leads to a crucial difference: passing on genes is a cooperative process rather than a competitive one. Even a predator-prey relationship is genetically cooperative, as the prey cell essentially transfers all its genes to the predator. In a sense, predation and reproduction are indistinguishable.

One surprising parallel between Earth and Kepler life is the genetic code. Both sets of life use the same nucleotide bases—guanine, uracil[9], cytosine, and adenine—to encode genetic information. This is not surprising; since both forms of life use RNA/DNA based nucleic acids, the alignments that produce strong hydrogen bonding between base pairs work the same way. Kepler's life includes two additional nucleotide bases beyond the four already discussed, and both these bases do not include nitrogen in their structures. This is also unsurprising, given the lack of nitrogen in Kepler's ecosystem.

The surprise is in the code itself. On both worlds, a triplet of nucleotides codes for a specific amino acid, and a sequence of these codon triplets defines the amino acid sequence needed to build a particular protein. And life on both worlds uses the same code. That is, the sequence AUG[10] codes for the amino acid methionine on both worlds. When the only life known was life that evolved on Earth, the specific codes could have been considered a product of happenstance. But with the discovery of two worlds using the same code, it seems evident that there is some biochemical advantage that these particular codes have over other combinations.

It may be difficult to understand how the two worlds can use the same code, yet Kepler's life includes two additional nucleotide bases. The key to understanding this is that the additional bases only appear in the third position of any codon. For example, if we use X for one of the additional nucleotides, AUX is an allowed sequence, while AXG is not. This fits with wobble theory, the idea that the first two bases bind strongly to the molecule reading the code[11] but the third does not. This allows for some variation in the coding sequences. Kepler's life seems to have taken advantage of this wiggle room by inserting nitrogen-poor nucleotides in places where they wouldn't alter the code.

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Getting Together

The mechanism leading to multicellular life on Kepler is open to debate. The predominant theory holds that multicellular life began as a result of Kepler's version of mitosis. Just like Earth cells, when a Kepler cell grows large enough, it can divide into two daughter cells. The process is made easier by the dispersion of pRNA throughout the cytoplasm; the cell can simply divide into two and be reasonably sure that both daughter cells will have at least one copy of each gene. On the off chance that a cell is missing a specific gene that it needs, it can simply engage in a gene transfer with its neighbor.

Thus, daughter cells had an incentive to remain close to their siblings. Those that formed tight clusters had a competitive advantage over those that didn't, and therefore were more successful at reproducing. Eventually, cells in clusters began to specialize—genes for photosynthetic molecules were shunted to cells near the surface, while deeper cells concentrated genes for other functions. In contrast to Earth life, however, cells could easily switch roles as circumstances required by simply importing and exporting the right pRNA strands.

At some point, genes evolved that were capable of regulating and directing the pRNA transfers.

This allowed multicellular life to really take off, as increasingly specialized director genes shepherded cells into increasingly specialized functions[12]. Eventually, this led to the development of specialized tissues and organs. What's unique about Kepler's life is that these specialized tissues are temporary; when a multicellular organism is unable to support itself due to lack of resources, it can simply transfer essential genes to some or all of its cells and allow them to go their separate ways. When conditions are right, director genes can again organize cells into a multicellular organism. The specific triggers for this, and the mechanisms by which the pRNA directors coordinate, are not well understood[13].

The result of all this is that taxonomy as a field of biology does not exist on Kepler. Earth life can be readily classified into kingdoms, phyla, etc., right down to genus and species. Early taxonomic schemes were based on superficial traits like appearance, but later systems used genetics as a basis for organizing living organisms. On Kepler, however, this is not possible, because each organism is made of cells with different sets of genes. In a very real sense, each organism is a species unto itself.

This means that no organism on the planet can be classified as plant, animal, fungus, etc. Gene transfers between organisms can allow each individual to take on any combination of roles that is required. A crawling organism can eat from a leaf-frond of an umbrella stalk, discard the chlorophyll genes, and keep the genes that produce the frond itself in order to produce gossamer wings. In other words, genes that allow cells to form into strong thin sheets can be adapted for use in wings, leaves, or other structures. As we continually see in life on Kepler, cooperation rather than competition drives evolution. Organisms have evolved little protection against predation; the predator-prey relationship is actually beneficial to both organisms because it simply allows for new combinations of genes.

Interestingly, reproduction remains a unicellular process on Kepler. In other words, multicellular organisms lack specialized reproductive systems. Since gene transfer occurs almost continuously, there is no need to evolve sexual reproduction as a way of reshuffling genes. Instead, reproduction occurs by simple mitosis, with cells splitting into two equal daughter cells. If an organism grows larger than it needs to be, it can simply shed excess cells as they are produced. Shed cells generally find their way into the soil, where they merge with the soil cell colonies. Eventually, these soil cells could be organized into new multicellular organisms, and the cycle of life repeats.

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The Soft Rains Come

One particular reproductive strategy proved devastating for the early colonists on Kepler. Cells carried high into the atmosphere can survive for years if they carry genes that allow them to thicken their cell membranes and go dormant. These cells remain dormant, emerging only to exchange genes during rare encounters with other cells, until the winds carry them into water clouds. The plentiful water brings new life to the cells, and they swell with water in preparation for mitosis. When conditions within the cloud are right for rain, the cells begin producing ribozymes designed to break down cell membranes. The ribozymes are stored within chitin-lined vacuoles which prevent them from damaging the cell's own membrane.

When the rain begins to fall, the cells release their enzymes into the raindrops. On the ground, any cells that are not protected by a chitinous cell wall are torn open by the enzymes. This provides a rich nutrient soup in the spongy soil for the cells that came down with the rain, and they immediately divide, absorb nutrients and genes, and divide again, repeating as often as they can until the resources run dry. The ribozymes themselves are fairly short-lived, denaturing after a few minutes.

This is part of the normal reproduction cycle for life on Kepler. Many cells carry genes for chitin and are protected from the ribozymes. Cells that require mobility may dispense with the cell wall, and others simply lack the gene needed to produce chitin. These cells are destroyed, but they pass on their genes to the newly fallen cells and so nothing is lost. It's simply another form of mutually beneficial predator-prey reproduction.

Human cells lack cell walls, and that lack nearly spelled disaster for the first colonists on

Kepler. The ribozymes are water-soluble and therefore quickly permeate exposed skin, breaking down cell membranes and killing the cells. The result is severe chemical burns on the skin. Worse, aspirated water droplets enter the lungs and damage cells in the alveoli. Most of the colonists who perished in those first rains died as a result of pulmonary edema caused by ribozyme burns inside the lungs.

Since plant cells are protected by cell walls, the ribozymes don't harm them. This is fortunate because it allows colonists to grow crops on the planet's surface. If this had not been possible, the colonists would have been limited to growing food in greenhouses, which would have severely inhibited the growth of the colony.

* * *

Anatomical Position

It's difficult to discuss the anatomy of Kepler's life forms because every individual organism is unique. But certain specific features are common, and their pRNA sequences are widely distributed throughout the ecosystem, at least in the parts of the planet that have been explored. Multicellular life in the area around the colony tends to a few major body types dubbed by the colonists as umbrella stalks, flitters, crawlers, and walking trees.

At first glance, umbrella stalks appear to be giant mushrooms, with a thick stalk capped by a thin umbrella-shaped leaf-frond. Most cells in these organisms possess chitinous cell walls, but the similarities to Earth fungi end there. The umbrella fronds are packed with photosynthetic cells, and in many individuals the stalks have cells along the surface that can also perform photosynthesis. The stalks themselves are occasionally surfaced in bark, probably obtained through gene transfer from walking trees, but most have stalks that are smooth and fibrous. They possess no roots; instead, the stalk extends into the soil and gradually merges with the soil cells. One of the most striking features of a stalk-forest is that the umbrella stalks arrange themselves into regular hexagonal grids. The reasons for this are not completely understood, but it seems to be another artifact of the cooperative nature of evolution on Kepler. In this case, it seems likely that director ribozymes determine the spacing that maximizes nutrient availability[14].

Flitters often have snake-like bodies up to half a meter long, but most are much smaller. Their wings are modified versions of umbrella stalk leaf-fronds. Wing size, shape, and structure vary dramatically from one individual to the next. Some retain photosynthetic function in the wings, but most expel those genes and rely on predation for their energy needs. The vast majority lack any sort of limbs and are thus incapable of landing. Their cells nearly universally lack cell walls, making them quite fragile but also very flexible. If one of these creatures is damaged or knocked to the ground, its cells simply rupture their own membranes, effectively transferring their genes to the nearby soil cells. Crawlers have similar body shapes, but they lack wings and instead use flexible limbs borrowed from walking stick genes in order to crawl or burrow.

Walking trees range in size from a few centimeters to ten or more meters in length. The smaller forms are often called walking sticks. These creatures almost always have a protective bark-like outer skin made of lignin-like polysaccharides. This rigid surface limits the rate at which the organism can grow, so excess cell growth is directed into long branches that grow out of the creature's dorsal surface. In some cases, these branches sprout photosynthetic leaf-fronds to supplement energy production. Flitters can often be seen feeding on branches, which helps the walking tree by transferring genes and keeping the branch from growing too large. The walking tree itself feeds by digging long furrows in the soil as it walks. The soil cells that are consumed readily decompose and add their genes to the walking tree's cells. Walking trees use their feet to either pierce or smash, depending on size, smaller organisms, allowing them to assimilate new genes.

The unique combination of rigidity and flexibility needed by walking trees and, to a lesser extent, flitters and crawlers, results from the presence of a pneumostatic skeleton and an ability to rapidly change turgor pressure. Many invertebrates on Earth, including earthworms and starfish, have a hydrostatic skeleton. These fluid-filled sacs provide structure and support and, surrounded by rings of muscle tissue, allow for body movement and locomotion. Organisms on Kepler have developed a gas-filled equivalent, a pneumostatic skeleton. Cylindrical sacs filled with pressurized air run along the center of the body and through the larger limbs of walking trees. By shunting air from one sac to another, the organism can bend at almost any spot along the body or limb. The skeleton also acts as a storehouse of atmospheric gases and a repository for gaseous wastes.

Turgor pressure occurs in cells that have cell walls. When the cell is fully inflated with water, the cell membrane presses against the cell wall, providing outward pressure. In Earth plants and fungi, this is the normal state of affairs. Wilting occurs when cells run low on water and lose turgor pressure. Plants like sunflowers and Venus flytraps use changes in turgor pressure as a means of achieving relatively rapid motion. On Kepler, walking trees and some other organisms osmotically adjust turgor pressure as a means of locomotion; cells along a plane in the limb decrease turgor pressure. This, in combination with the contraction of muscle-like polysaccharide fibers around the pneumatic skeleton, causes the limb to bend. It takes some time for the cells to replenish their fluids and restore turgor pressure, so the limb bends at a slightly different point on the next step. While this mechanism doesn't provide the range of motion or speed seen in Earth's animals, it does provide a great deal of flexibility to the organism's movement.

* * *

Is Anyone Else Out There?

For all of human history, biologists were limited to studying a single life-bearing world. With the discovery of life on Kepler, some long-standing questions can be put to rest. Life on Earth was indeed more than a chemical fluke, nucleic acids do seem to be nature's go-to molecules for inheritance, and the oxidation of sugars and fats is the primary method of generating biological energy.

But for every question answered, dozens more have arisen. Was the switchover from pRNA to RNA on Earth a random accident, or was there some environmental factor on Earth that isn't present on Kepler? Is the overlap of genetic codes on the two worlds a simple case of convergent evolution, or is there some biochemical mechanism that requires life everywhere to use that same code? The discovery of life on other worlds would surely shed further light on these questions, and likely bring up new mysteries that we can't yet imagine.

Footnotes:

[1] Translation: the author doesn't want to be pinned down to a specific star!

[2] Like the Kepler colonists, I'm going to use the terms perihelion and aphelion, even though they technically refer only to Earth's sun. I do this because the distinction is irrelevant to colonists who will never again return to Earth and, more importantly, I find terms like periapsis or periastron to be ugly and just plain yucky.

[3] This process is called glycolysis. While the overall process of converting glucose to acetate units is the same on Earth and Kepler, the biochemical pathways are quite different. This is likely a case of convergent evolution.

[4] Biologists call it the Krebbs cycle, chemists prefer the term citric acid cycle. We're all chemists here, right? And if you're one of those people who calls it the tricarboxylic acid cycle, well, we can't be friends.

[5] That's a fancy way of saying that the reactions as described can't provide sufficient energy to support multicellular life. Kepler life must have some additional processes to make it viable, but I didn't need to get into that in the novel. Heck, a lot of the stuff I already worked out never made it into the story directly. That's what makes these "science behind the story" articles so much fun; I get to unveil all those hidden details!

[6] Imines are compounds that contain a carbon atom double bonded to a nitrogen. If you break the double bond, you get an amine. Then all you have to do is add a carboxylic acid group to the molecule and you have an amino acid. Kotori never had a chance to figure this out in the novel, but give her time.

[7] See the C=O group at the top? That's called a carbonyl group. The carbon chain can wriggle and twist, bringing one of the -OH groups near the end of the chain close enough to react with the carbonyl group. They bond together, forming a ring.

[8] Some ribozymes still exist, like the rRNA in ribosomes that facilitates protein synthesis.

[9] Uracil is used in RNA, thymine replaces it in DNA. The difference between the two is an added methyl ($-CH_3$) group on thymine, which helps to stabilize the DNA molecule.

[10] This is the shorthand biochemists use to list the bases within a codon. AUG stands for adenine, uracil, and guanine. This combination of bases, in this specific order, is the code that tells the cell to insert a methionine molecule into the protein it's building.

[11] In Earth life, this is a transfer RNA, or tRNA, molecule. On Kepler, that role is filled by a ribozyme that combines the functionality of tRNA and ribosome.

[12] This is another thing that Kotori hasn't yet discovered. There's only so much you can cram into a novel before it gets bogged down!

[13] Which, or course, means that the author doesn't know.

[14] This is another aspect of Kepler's life that I wanted to explore further. At first some colonists thought the regular spacing was a sign of intelligent life on the planet. They never did figure out the reasons for it and who knows, they may have been right in a sense. Is it possible for a network of ribozyme directors to coordinate an entire ecosystem in a purposeful, intelligent way? Could the entire system become self-aware?

Jay Werkheiser started writing science fiction stories as soon as he was old enough to put pencil to paper. No one stopped him, so he kept writing, and somewhere along the line his stories became good enough for publication. He writes primarily hard science fiction, but isn't above the occasional time travel or light-hearted sci-fi comedy. After years of claiming he was exclusively a short fiction writer, Jay finally gave in to the temptation to write novels. Kepler's Laws *is his first novel. When he's not writing, Jay teaches chemistry and physics to eager high school students.*