To Moldly Go

[Slow version of theme song begins]

Izzie: [In a scratchy radio effect] Space. The final frontier. These are the voyages of the Sporeship Enterprise. Its continuing mushroom: to ex-spore strange new worlds. To seed out new life and new lichenizations. To moldly go where no one has gone be-spore!

[In a normal voice] Welcome to Morel Dilemma, an exploration of why some fungi are so highly sought, some are so heavily cultivated, and some are so very dangerous. Today we're continuing our theme of topics apparently unrelated to modern fungi. In the last episode, I talked about fossils, which sounds like a weird topic for a mushroom podcast until you learn how important ancient fungi were in *molding* the world we know. Now, it's time to address the real beginnings of life (maybe) and the future of life. Today's topic is fungi… in *spaaace*.

[Music ends]

Izzie: Fossils tell us a lot about how fungi helped craft our modern world, from making dry land livable to establishing their all-important role as nature's recyclers; but they don't tell us where and how fungi, and indeed all life, actually developed. While we don't actually know how life first arose, the leading theory is that it was an accident. Atoms naturally arrange themselves into molecules, and molecules move into and around each other to make new molecules and new arrangements of molecules. At a certain point, after no small amount of random motion, certain early molecules meshed together in a way that allowed for the storage of information, creating early DNA. Certain other molecules arranged themselves into rows and spheres, making early membranes that could separate the DNA from the environment. Slowly, and probably not all at once, the first cells developed.

[Music begins]

Izzie: Stephen Hawking calls this idea of spontaneous life extremely unlikely, but compares it to winning the lottery: just because something is extremely unlikely does not mean that it can't happen. Lab experiments have demonstrated that soups of the right molecules do form membranes spontaneously, and non-biological chemicals can spontaneously generate amino acids, the building blocks of proteins. New life has never suddenly appeared in a lab study, but theoretically, the idea is sound. Now the question becomes: when and where has it happened?

[Music ends]

Izzie: The Big Bang that started our universe off happened about 14.6 billion years ago, but Earth is only about 4.6 billion years old. Despite the incredible age of the rest of the Universe, it's Earth – a cosmic infant – where the only life we know of exists. If life's origins were just an issue of random chance, it seems unlikely that our little blue marble was the only lucky shot in the universe. It's much more likely that sometime in the 10 billion years between the Big Bang and the Earth's formation, random chances gave birth to life *somewhere else*. This notion is known as *panspermia*, with *pan* meaning "everywhere" and *sperm* meaning "seeds".

[Music begins]

Izzie: There are a number of variations to panspermia. Ballistopanspermia is the theory that massive meteor impacts can knock life away from its home and into space, and that it can travel between planets that orbit the same star. Lithopanspermia theorizes that organisms can move between star systems by the same random mechanism. On the other hand, directed panspermia is the idea that advanced civilizations could intentionally spread life to other planets or star systems. The idea of colonizing Mars with humans would be an example of directed panspermia.

Of course, panspermia doesn't address the question of what made life possible in the first place. It just gives the first life in the *entire* Universe longer to develop, and makes it easier to presume that there's other life out there. Even if Stephen Hawking is right, and the development of life is the jackpot of the cosmic lottery, panspermia would allow a single stroke of colossal luck to result in a universe full of life. And in that case, we Earthlings are not only far from unique, we aren't even necessarily the originals.

[Music ends]

Izzie: Although it sounds like modern science fiction, the idea of panspermia is actually about a century old. The theory was formally proposed in the early 1900s by Swedish chemist Svante Arrhenius, who believed that microorganisms could develop in different places in the cosmos at different times, whenever conditions were favorable. For example, when our solar system was young and the Earth was still molten rock, Mars had a fairly modern-Earth-like atmosphere. In Arrhenius' panspermia, life could have developed on Mars, then either moved to Earth or independently developed here once conditions were favorable. Arrhenius didn't bother with ballistopanspermia, the idea that microbes need to travel on rocks between the planets, but thought that they could be pushed around solar systems by the power of star-emitted light alone.

Since Arrhenius, there have been a number of people who independently proposed the theory, and today there are many outspoken proponents – and opponents – of panspermia. In researching this episode, I found a lot of scientists who are really hoping that there's life out in space, and would love to know about it, but haven't yet seen enough evidence to convince them that panspermia is the way things are. To paraphrase Carl Sagan, if panspermia is to be accepted in the scientific community, then there needs to be "extraordinary evidence" supporting it in all of its aspects: the idea that life can form other places, the idea that it can move between planets or stars, and that it can land and survive somewhere new.

[Musical tone]

Izzie: To begin with, panspermia assumes that life can survive on other celestial bodies – planets, moons, or asteroids. In the amazing TV series "Into the Universe with Stephen Hawking", Hawking even suggests that there could be life in places we'd never think to look for it, like in deep space or the center of a star. But Hawking also thinks there is plenty of the sort of life we *would* look for – life that relies on water and carbon. Since the laws of physics are the same in the distant reaches of space as they are in our solar system, the laws of chemical life, which relies on the same physics, might also be universal. I highly recommend watching the series, because Stephen Hawking has some really incredible ideas and the visuals are awesome reflections on his theories. Also, it's narrated by Benedict Cumberbatch. What could be better?

Anyway, if we assume that physics makes life universally possible, then how might we be able to find it? At the Search for Extraterrestrial Intelligence, or SETI, Institute, scientists look for light and radio waves that could be coming from other advanced life, at our level of intelligence or possibly higher. But at a basic level, those who study the potential for life in space, called astrobiologists, begin their search with liquid water or a water-like liquid.

[Music begins]

Izzie: Frozen water is actually pretty common in the universe; it's liquid water that's harder to find, and liquid water that allows life as we know it to exist. The "Goldilocks Zone" is the nickname astronomers use to refer to the narrow region around a star in which the temperatures would allow some life-sustaining liquid to stay liquid. There are actually two potential Goldilocks Zones around most stars. One, like the zone Earth occupies, allows for liquid water. The other band, much further out, allows for liquid nitrogen, which has physics similar to those of water – at negative 350 degrees Fahrenheit. Liquid nitrogen-based life is theoretically possible, but would use silicon for all the things we use carbon for, like sugar and the backbone of DNA.

[Music ends]

Izzie: In our solar system, both Earth and Mars are orbiting the sun in its Goldilocks Zone, which is why scientists think Mars is such a good place to start looking for extraterrestrial life. There are other favorable similarities. The earliest known Earth life were bacteria that lived off of iron in hydrothermal vents on the ocean floor, 4.2 billion years ago. Earth was about 300 million years old at that time. Well, we know from the color of Mars' soil alone that the planet is very rich in iron. And the geological history of Mars is apparently very similar to that of Earth. So if ever there was liquid water on Mars, scientists might be able to look into Mars' past when it was only 300 million years old, and look for evidence of life in hydrothermal vents that would parallel those bacteria from Earth.

Believe it or not, though, there may be liquid water somewhere else in our very own solar system, 30 million miles beyond Mars.

[Music starts]

Izzie: Europa is one of Jupiter's many moons, and it's slightly smaller than our moon. Europa's surface is a layer of water ice believed to be at least fifteen feet thick – which is no surprise, since the temperature way out there is about negative 260 degrees Fahrenheit. While that's not nearly cold enough for liquid nitrogen to flow, underneath its surface, Europa may be an ocean world. Europa has an elongated orbit, which means that the pull of Jupiter's gravity doesn't affect it consistently. The alternating stretching and compression would provide enough heat to keep the theorized salt oceans above freezing temperature, and could result in life-friendly hydrothermal vents erupting below the surface.

[Music ends]

Izzie: Extending our gaze beyond our own solar system, there are many planets and moons that could potentially host life. The first planet outside our solar system was discovered in 1995, and there are currently 52 known planets that occupy their Goldilocks zones, probably have liquid water, and possess an Earth-like atmosphere. With our current technology, though, we're unlikely to be able to visit any time soon. That's why, though there may be habitable or life-harboring planets around other stars, or at the extremes of our solar system, most of the focus remains on Mars.

[Music begins]

Izzie: There is no liquid water on Mars currently, so it's generally considered unlikely that there's any life thriving there. However, Mars has ice caps at the poles, and many geological patterns on the planet's surface are suggestive of erosion and water movements known from Earth. More direct evidence came with the Spirit rover, which landed on Mars in 2004. In and among its wanderings, Spirit found white salts beneath the soil of Mars – and such salts can only form in the presence of liquid water or liquid carbon dioxide. The ice caps, signs of erosion, and the presence of these salts all contribute to the ever-increasing body of evidence that Mars once harbored liquid water. Perhaps in Mars' ancient days, that water teemed with life.

[Music ends]

Izzie: If there was life on Mars – a question I'll cover in more depth later in this episode – then there could still be life there, and not just in fossils. Many Earth organisms are extremely hardy and can survive with little to no water. Permafrost ecosystems at Earth's poles are made up of microbes that live on very thin films of water in otherwise frozen soil and ice. There is also microscopic life in the Atacama Desert of Chile, which has soil very much like that of Mars and has actually been used by NASA to test Mars rovers. The Atacama is the driest desert in the world, besides our poles. Some areas in the Atacama can go more than four years without rain; other areas may have never received rain at all. Records show that the Atacama may have received no significant rainfall in the 400 years between 1570 and 970! And there's life there! Would it be so hard to believe, that microbes could survive on today's Mars, as dry as it may be? And could the precursors to those extremely hardy microbes have given rise to life on Earth?

Astronomer Royal Sir Martin Rees – who advises the Queen and the British Royal Family on matters of astronomy, which sounds like a super awesome job – believes that life could have evolved independently on Earth and Mars, but finds it unlikely that one seeded the other. On the other hand, senior SETI astronomer Seth Shostak thinks that Earth life may have originated "in the vanished seas of Mars" – but doesn't think that panspermia could bring life to Earth from further away.

Well. We'll see about that.

[Intermission music]

Izzie: So if life on Earth did come from Mars – or from further away – how would it have gotten here? I have divided the voyage of life through space into four steps: in Step One, the life needs to get off the source planet, ideally inside a protective material like rock. In Step Two, the organisms must survive their journey through space. In Step Three, they must survive the impact to a new planet, and finally, in Step Four, they need to be able to live, thrive, and reproduce in their new home.

[Musical tone]

Izzie: In Step One, we need a rock to escape from its planet, with life inside. Getting life in there isn't too hard, actually; microbes are super small and can work their way into apparently solid rock, and of course fungi crunch through rock on a regular basis. Rocks, in turn, would offer the microbes a protected environment (just *how* protective, we'll address in Step Two). If it's porous, a rock could even potentially have some moisture, which could protect microbes from drying out on their long journey. But how does the rock get off the ground?

There are definitely rocks bopping between planets in our solar system, because there are meteorites on Earth that came from the moon and Mars – which we know because scientists were able to compare the meteorites with rock samples from space missions.

[Music begins]

Izzie: The *escape velocity* of a planet is the speed at which an object has to travel to escape the planet's orbit, and not be pulled back in. For Earth, that speed is about seven miles per second; for Mars, it's about three miles per second; and for the moon, it's just one and a half miles per second. There are only two things we know of that could launch a hunk of rock away from a planet that fast. One is massive volcanic activity, but it would require a volcano with more oomph than any we have on Earth. The eruption velocity of our volcanoes is only half a mile per second, not even enough to get a rock off the moon. The other thing that can knock a rock off a planet is … a bigger rock. From space.

When a massive meteor or asteroid hits a larger rock, like a moon or a planet, the force of the impact sends up a ring of *ejecta*, which literally just means "ejected rock". Imagine throwing a marble into the sand, only bigger. Some of the ejecta goes out to the sides of the impact, creating dramatic crater rings like you see in the movies. But close to the site of impact, the energy of the shock wave is so great that ejecta are launched directly upwards.

There's a marvelous example from our own planet's history. You may have noticed that there aren't any dinosaurs walking outside your window. Most scientists believe that, 65 million years ago, the dinosaurs and most other Earthlings were wiped out, either directly or indirectly, by the impact of a massive asteroid, more than nine miles across. The Chicxulub Impact crater on the Yucatan Peninsula, 110 miles across, is the result. Particularly massive objects like that one could launch millions of rocks, up to meter-long boulders, into space and out of Earth's gravity within *half a millisecond!* But as unbelievable as it sounds, the impact would have caused little shock damage to rocks close to the surface – or to the life harbored inside them.

[Music ends]

Izzie: Rocks can handle pressures of almost 150 pounds per square inch before their pores collapse, and without being heated above the boiling point of water. So any larger life would definitely be squished, but if microbes could survive the acceleration, they wouldn't need to worry about being crushed or boiled alive – which is, you know, nice. Several studies have addressed microbe survival at high speeds, and the outlook is surprisingly good. In one lab study, bacterial cells survived accelerations up to 25 times higher than they would need to live through ballistic ejection from Mars. Another study found that bacteria could withstand pressures 15,000 times Earth's gravity, apparently indefinitely. The acceleration in the lab is much slower than the half a millisecond that would be experienced in an actual ballistic launch, but such studies demonstrate that bacteria, at least, could probably handle it.

[Musical tone]

Izzie: Step Two for our brave ex-spore-ers is survival in the dark reaches of space. For this mission, bacteria and fungi alike would rely on spores. So-called bacterial "spores" are more accurately called *endospores*. These are basically dormant cells that bacterial species use to withstand extreme environments. Bacterial spores are some of the hardiest known lifeforms. They have no detectable metabolism and are much more resistant than normal bacteria to both wet and dry heat, radiation, and extremely dry conditions, including vacuum. In addition, they are resistant to a lot of biologically created degraders, like digestive enzymes, as well as toxic chemicals, like strong acids and bases. When they have withstood basically everything the universe can throw at them, and favorable conditions return, endospores rapidly turn into normal bacteria and start living average bacterial lives. Fungal spores are, of course, just spores – little packets of genetic information, also ready to withstand just about anything until they land somewhere favorable and start growing hyphae.

[Music begins]

Izzie: Both endospores and fungal spores have proven to be extremely resistant to all the stresses of space travel, including extreme acceleration, extreme desiccation (dryness), zero gravity or microgravity, and very high UV and gamma radiation. In

1993, up to 70% of both bacterial and fungal spores tested survived a 10-day experiment, unprotected, in the vacuum of space. Not impressed? Neither were Doctors Horneck, Bucher and Reitz, who in 1994 published the results of a six-*year* experiment exposing the spores of *Bacillus subtilis* bacteria to the void of space, on the outside of the International Space Station. Also not impressed were Doctors Hasegan, Mogildea and Mogildea, who in 2016 reported the results of *their* six-year vacuum-of-space study, this time looking at fungi.

The fungi were selected based on their strong performance as decomposers, degraders, and potential contaminants that could either help or seriously hinder future space colonization attempts. The bacterial spores were selected for… well, for the fact that basically everyone tests survival on *Bacillus subtilis* spores. They're good at what they do! In both studies, the groups in space were compared to groups of the same organisms in space simulation chambers on Earth. Here are their results, starting with the fungi, because of course I am.

The fungi were not only able to grow in microgravity, the very weak gravity felt on the ISS, they were also able to continue decomposing organic materials as long as they were supplied with water. The aboveground mycelia, the part that could eventually turn into a fruit like a mushroom, stopped growing after less than a week, as the fungi focused on growing mycelia through their food source instead. This means that fungal activity, like decomposition, is high in microgravity, while their spread is low – because only the aboveground mycelium can fruit and sporulate, and it isn't as active. In space, the fungi don't sporulate until their hyphae feel some mechanical pressure, like the edges of their food container. That means they could be a useful means of recycling on long colonization trips, and wouldn't necessarily sporulate and spread to where they aren't wanted. And as for the spores themselves, dry fungal spores kept in microgravity for five months were still viable – which is also a bit more support for the idea of panspermia.

[Musical tone]

Izzie: The bacterial study on the ISS made use of the NASA Long Duration Exposure Facility, which is sort of an unenclosed bubble on the side of the space station. The bacterial endospores were put out there either with a shield to protect them from radiation, or without one. The endospores were either spread out in a monolayer or stacked in multiple layers. The endospores on the outside of the multilayers died quickly, presumably because they are more exposed to the extremes of space, but one to two percent of those multilayer spores survived, using the dead husks of the outer spores as a shield against radiation and desiccation, which is pretty metal. A greater proportion of the monolayer spores survived. Endospores in both groups benefitted significantly from an environment rich in sugar and salts – which gave enough protection to keep a whopping 70% of the endospores viable for six years in vacuum!

It turns out that the shields were the greatest boon for the study's spacefaring bacteria. In the words of the authors, space in general is "extremely hostile to all forms of life," and the radiation emanating from stars is even more destructive than vacuum. Even endospores shielded from 70% of the UV radiation had rates of survival 1000 times lower than endospores that were fully covered. So apart from giving microbes a ride in the first place, UV protection is one of the greatest favors a rock can offer during ballistopanspermia.

Fortunately for mycophiles like myself, many fungi have an absurd capacity for dealing with radiation.

[Music begins]

Izzie: Tamas Torok, of Lawrence Berkeley National Laboratory in California, has a collection of more than 2,000 fungi gathered from around Chernobyl in the late 1990s. These fungi didn't just grow inside the so-called "exclusion zones", where the radiation levels are most dangerous; they actually grew towards Chernobyl itself, the center of the radiation. Dr Torok has studied the fungi to discover what makes them so resistant to that extreme radiation. They contain a whole lot of melanin, the sun protective molecule that also makes human skin darker, which makes fungi dark and absorbs a lot of the radiation – such that the mushrooms closest to the reactor are completely black. And also, those fungi closest to Chernobyl were using the normally-lethal gamma rays as a source of energy! That's right: they took toxic levels of radiation and decided to make lunch out of it. This is why fungi are my favorite. And according to NASA Jet Propulsion lab scientist Kasthuri Venkateswaran, this is evidence that Earth fungi may be able to survive through spaceflights.

[Music ends]

Izzie: Dr. Horneck and the other scientists who ran the six-year bacteriastronaut study warn that we shouldn't extrapolate the results of a 6-year study to the time periods that microbes might have to spend in space to participate in panspermia. Seth Shostak, senior SETI astronomer, says that in the early solar system, Earth was pummeled by billions of rocks originating from Mars, and anywhere from one inch to one yard across. Depending on when they were expelled from Mars, the points in various planets' orbits, and other factors, the rocks may have reached Earth in as little as one year – well within the timeframe of the studies we're talking about – or in as much as one million years, which is much harder to extrapolate to.

We have to take the results of the space studies with a grain of salt, and I think that's a good piece of advice for the Chernobyl mushrooms, too. After all, the space studies were performed on or in the ISS, which could offer some protection that wasn't accounted for in the studies. And the fungi at Chernobyl had decades to evolve radiation resistance while they grew on ample food sources, had access to water, and reproduced to introduce new diversity into the population – all luxuries which dormant spores on an asteroid wouldn't have.

[Music begins]

Izzie: But theoretically, bacterial endospores and fungal spores can survive in microgravity and even vacuum for at least 6 years, and fungi are so awesome they can actually take the most harmful characteristic of space travel, solar radiation, and turn it into food. Also, the six-year ISS studies simulated a straight path 600 billion miles long – the distance from Earth to Saturn, as the space-crow flies. So based on those studies, fungal and bacterial spores have a fairly good chance of surviving in space long enough to reach another planet, and Step Two is complete.

[Music ends]

Izzie: Step Three of getting organisms to a new planet is making sure they survive their rock's sudden impact. For a rock hurtling through space, about to reach an abrupt stop, a planet with an atmosphere provides a comparatively cushy landing. It only takes about a minute for a spacefaring object to pass through an atmosphere like Earth's, which is long enough for small rocks to completely burn up from friction, but is too short a time to heat the inside of a large rock – in fact, most large meteorites are cold to the touch when they land! Many of the meteorites that come to Earth from the moon or from Mars show no evidence of heating beyond their melted outer crust, which is one tenth of a millimeter thick. One Martian meteorite, ALH 84001, has not been heated above 104 degrees Fahrenheit in its entire 4 billion-year lifetime, despite having had to leave Mars and enter Earth's atmosphere. The air resistance also means large objects slow down considerably before impacting the planet's surface, and may break up into smaller fragments that get distributed along the ground of the new planet. If the meteorites toss up ejecta, that can help get any harbored microbes mixed in with their new substrate. But would they still be alive at that point?

[Music begins]

Izzie: There aren't many experiments looking at fungal spores surviving the kind of short, sharp shock they would experience crashing to a planet, but a few studies have investigated bacterial endospore survival in similar conditions. In one experiment, researchers embedded bacteria in different materials, then shot them out of a cannon. Whee! The bacteria reached an acceleration of 33,800 times Earth's gravity within one millisecond! Most of the bacteria survived, regardless of their containing material, but *Bacillus subtilis* won the day with 100 percent survival. Another experiment, utilizing explosives, subjected *Bacillus subtilis* endospores to almost 320,000 atmospheres of pressure – which is almost 5 billion pounds per square inch. Incredibly, about one-thousandth of them survived… which is more than you could say for, like, *people*. There's even an evolutionary reason why Earth bacteria might be so well adapted to high pressures. As I mentioned earlier, the first known Earth life were hydrothermal vent bacteria, and hydrothermal vents are more than a mile below sea level, and pressures there can exceed 200 atmospheres – or 2900 pounds per square inch! I'd say chances of surviving an impact are pretty good. I'm going to call Step Three complete.

[Music ends]

Izzie: In Step Four, our spacefaring microbes need to survive on their new home. Fungal spores, freshly emerged from microgravity, could grow and begin fruiting again if they landed in a favorable location. Bacterial endospores wake up from dormancy when they encounter favorable conditions; hundred-thousand-year-old bacterial spores (from Earth) have been successfully reanimated, so a little jaunt in space isn't unreasonable. And newly emerging spores might even have greater survivability on the new planet than they did in space; endospores coming out of dormancy have an even higher resistance to UV radiation than dormant spores, for a short time.

[Musical tone]

Izzie: Overall, rushing headlong from an impact blast on one planet to smack into a new one is a surprisingly reasonable journey for microbes. Bacterial endospores can definitely survive the incredible acceleration they would experience getting off a planet; spores and endospores can handle the vacuum of space and microgravity conditions for at least half a decade if they are protected from UV radiation; and they can survive impact to a new planet as long as there's an atmosphere and they're inside a protective rock. Considering all the evidence and all the models, SETI astronomer Seth Shostak says panspermia is a "credible" theory over short cosmic distances – like, between planets in one solar system, but not necessarily between stars. I have to say I agree.

[Intermission music]

Izzie: So now that we know that the puzzle pieces all line up, we can start evaluating the theory of ballistopanspermia a bit more deeply. Like, first of all, figuring out how similar extraterrestrial life could be to our own.

[Intermission music ends]

Izzie: Scott Hubbard, the first Mars Program Director at NASA, argues that "Direct life detection is inherently difficult …because there is no uniform agreement on life". This goes back to Stephen Hawking's TV special theorizing life inside stars or in deep space, life forms we wouldn't necessarily understand as alive. But for those forms of life that are more like us, there may be some ways to differentiate their extraterrestrial origins on a chemical level. Life relying on silicon instead of carbon would be a dead giveaway, as would any life that relied on liquid nitrogen instead of water. But there are subtler cues, too.

Astrobiologist Chris McKay, who works in NASA's Ames Research Center, suggested that he would be convinced of extraterrestrial life if he were presented with life that used amino acids of a different chirality from ours. *Chirality* means "handedness" in Greek, and there are right-handed and left-handed molecules. All life on Earth uses left-handed amino acids, the building blocks of proteins. McKay says that if we found cells that used right-handed amino acids, it would be solid evidence that the cells had extraterrestrial origins.

More amino acid evidence could come by way of meteorites.

[Music begins]

Izzie: As I said earlier, some amino acids spontaneously generate from soups of the right chemicals. Not all of those amino acids are useable in Earth life. In fact, there are a few amino acids that are only or chiefly known from meteorites – which of course means that they are extraterrestrial in origin. Hundreds of amino acids were found in the Murchison Meteorite, a famous meteorite *older than the sun* that landed in Victoria, Australia in 1969. The Murchison Meteorite is a type of meteorite called carbonaceous chondrite due to its high carbon content and its internal structure of small grains, or *chondrules*. Such meteorites have much higher organic material and water content than most – the Murchison Meteorite is 10% water and a whopping 2% organic material (the amino acids). We know that the unusual amino acids came from space because they are present inside the melted surface of the meteorite, which "sealed" the amino acids in during the trip through the atmosphere and separated them from potential Earthly contaminants.

The amino acids that arrived on Earth in the Murchison Meteorite are exceedingly rare on Earth, and in fact two of them, alpha-amino-isobutyric acid and racemic isovaline – I don't know those; I just read them really fast – are almost exclusively known from carbonaceous chondrite meteorites. Those two amino acids are also known from the layer of Earth's fossil record that marks the asteroid strike that killed off the dinosaurs.

[Music ends]

Izzie: Of course, if *all* Earth life derived from spacefaring ancestors, then there might not be anything chemically obvious to set ET life apart. Imagine if there is indeed life on Mars right now, but it has a carbon backbone and its DNA has the same structure as ours. It would just look like some Earth microbes hitched a ride on the probe and contaminated the samples. In fact, if life in space is biochemically identical to life on Earth, Chris McKay says it might be "impossible" to ever conclusively prove that it's truly extraterrestrial. On the other hand, Seth Shostak argues that the best evidence for panspermia would be finding DNA-based life somewhere besides Earth – so he thinks the distinction might be possible.

This debate almost had a trial by fire a few years ago – when it was discovered that Curiosity, the Mars rover launched in 2011, had not been perfectly sterilized before launch. A box containing some drill bits was opened after final sterilization procedures, so one of the bits could be adjusted, and another full sterilization step was not performed afterwards. Although the bit was adjusted in a very clean environment, there is some nonzero chance that Earth life hitched a ride on Curiosity inside this box. The mistake wasn't discovered until after Curiosity's launch, but wasn't expected to cause much of a problem; Curiosity's landing targeted a crater with no surface ice, and the rover wasn't expected to drill deep enough to hit any potentially life-supporting ice that might be hiding underneath the soil.

This is good for two reasons: First, it shouldn't be possible for any Earth life to contaminate Mars and upset any native ecosystem that might exist there. This is what Randall Munroe, mathematician and author of the famous webcomic XKCD, calls the "ethical" reason for sterilizing our probes. Second, Curiosity's mission was to look for evidence of water erosion, not evidence of life. So even if some microbes tagged along on Curiosity, they wouldn't be "discovered" on Mars. Randall Munroe calls this the "practical" reason for sterilization: if our probes are fully sterilized, we should know that any life we find is definitely extraterrestrial in origin. Of course, Curiosity's contamination is still a big issue, and has been addressed. But the practical problem of differentiating extraterrestrial life has been pushed to a later date – later than Curiosity's launch in 2011, and later than now, 2017.

[Musical tone]

Izzie: We haven't needed a definitive means of separating Earth life from other life because there still isn't any extraterrestrial life that we *know* exists. The closest we have come, in terms of location, theory, and evidence, is our old friend Mars.

Gilbert Levin is the greatest proponent of Mars life. He has published dozens of papers about life on Mars, many based on the test he designed for the 1976 Viking Lander mission, which is the only Mars mission ever to find apparent evidence of life. In the test, called the "labeled release" or LR experiment, radioactive nutrient solution was squirted onto the Martian soil, where organisms, if present, would metabolize the solution, producing radioactive carbon dioxide as a waste product. The probe would then heat the sample to turn the carbon dioxide wastes into a detectable gas. Presence of the radiolabeled gas would, hopefully, indicate active microbes in the soil. And in fact, radiolabeled gas is what the probe found! So why doesn't everyone already know about the life – real life – that exists on Mars?

[Music begins]

Izzie: Well, the results of the LR test weren't backed up by the Viking Lander's other tests designed to detect organic molecules, leading other scientists working on the Viking to propose that an unknown chemical process in the soil was breaking the nutrients down inorganically. As in, life wasn't doing it. However, although some geochemists have gotten similar readings, repeated lab studies have never replicated the results of Levin's test. Levin thinks it's also important that the soil samples stopped giving off the radiolabeled carbon dioxide when heated to temperatures outside of the livable range of most Earth organisms; he theorized that the microbes were killed at those temperatures, which might be why they didn't respond to subsequent tests.

[Music ends]

Izzie: In support of Levin, the other instruments on the Viking Lander have been called into question – because while they were cutting edge at the time, the technology was very limited compared with what we have today. Jeffrey Bada, director of the NASA Specialized Center for Research and Training in Exobiology, has found that there could have been many millions of bacteria per gram of Martian soil and the Viking probe would have been unable to detect them. The LR probe itself was extremely limited, only able to detect the very end product of metabolism. It couldn't catch other products, especially metabolic intermediates, which do not turn to detectable gas when heated but would have more convincingly established that the nutrient solution was being processed by living organisms. Unfortunately for Levin, and panspermia enthusiasts, none of the more recent rovers have found similarly compelling evidence for life on Mars.

[Musical tone]

Izzie: Clearer evidence could be hidden inside a Mars rock that isn't quite Martian anymore. About 3.6 billion years ago, a meteorite impact launched a rock out of Mars orbit and on a 3.5 billion year journey. Thirteen thousand years ago, it hit Earth – Alan Hill, Antarctica, to be exact. It was discovered in the late 1980s and dubbed Alan Hill 84001, or ALH 84001 for short. This meteorite is another carbonaceous chondrite, the class of space debris that is unusually high in water and amino acids , but this is the first one that apparently has full cells inside.

In 1996, a group of scientists led by David McKay, chief scientist for Planetary Science and Exploration at the Johnson Space Center at the time, announced that they had found structures in ALH 84001 that looked like fossilized bacteria. Since the rock dates back to a time when Mars had a thicker atmosphere, and probably had liquid water, it might actually be reasonable that it would contain life – especially because there are signs that the rock itself once harbored liquid water.

The scientists performed a lot of tests to make sure the supposed microbes weren't Earth contaminants, or simply mineral deposits, before publishing their findings, but critics still had plenty to say.

[Music ends]

Izzie: Dr. Schopf, a paleontologist of early Earth life, wrote that inorganic processes can make tubular structures that look like the supposed cells of the meteorite, which are also much smaller than the ancient Earth bacteria they would be expected to parallel. There was also very little evidence of a life cycle; the size of the supposed microbes had very little variation, and there was no evidence of any of them caught in cell division or other types of reproduction. McKay and his team argued that individually, the chemical or physical features of ALH 84001 might not imply life, but taken as a whole, and considering their proximity, they did. For example, some minerals that usually can't deposit or form in the same conditions, because one requires a basic environment and another requires an acidic environment, are adjacent in the meteorite. McKay's team believes this to be evidence that the minerals were created by living organisms rather than random chemical processes.

There was another extraterrestrially oriented fuss in 2011, when ex-NASA scientist Richard Hoover claimed to have found fossilized microbes in a different meteorite. However, the study was not published by NASA, but by the online Journal of Cosmology, which has a… colorful past, and isn't fully recognized in the scientific community. His paper was full of holes, and so, incidentally, was the meteorite – a very porous rock which many astronomers and microbiologists agree would have been easily contaminated by Earth life. In general, Hoover's claim was much more poorly received than McKay's paper concerning ALH 84001.

The fuss over ALH 84001 has largely died down, but that controversial study marked a new era in the search for extraterrestrial life. ET started being taken a little more seriously. And Mars is a huge planet – just because our small handful of rovers haven't found anything definitive yet doesn't mean there isn't, or wasn't, life up there. Many scientists from varying fields hold out hope, waiting for some real solid evidence that there's other life out there. Stephen Hawking thinks that finding microbes on Mars would be "one of the most exciting discoveries ever made".

[Musical tone]

Izzie: So we haven't found any space life *in space*, but we've found potential evidence for it in the rocks that rain down on Earth from elsewhere. Has extraterrestrial life ever come to Earth that we *know* of? The short answer is no. But the long answer… is also no. It's a more interesting no, though, that takes us to the stratosphere.

[Music begins]

Izzie: The stratosphere is the layer of Earth's atmosphere between about 9 and 23 miles above the planet's surface. It's above the troposphere, where all the weather happens. In weather balloon studies, scientists have repeatedly found microorganisms of various kinds, including both bacteria and fungi. A 2009 paper led by a Dr. Shivaji found twelve bacterial strains floating as high as 25 miles above the ground, which is four times the cruising altitude of a passenger jet. A paper published in 2013 reported that hailstones often contain some species of bacteria that are usually found on plants, as well as "thousands of organic compounds normally found in soil". The bacteria and fungi way up there are still alive, and protected by melanin and other pigments. Some of the bacteria in these papers were previously unknown, which led some scientists to suggest that they are extraterrestrial in origin. Okay, three scientists suggested that.

[Music ends]

Izzie: Doctors Wickramasinghe, Hoyle, and Wainwright are famous – or maybe infamous – for their efforts to demonstrate that extraterrestrial life is already here. In the year 2000, Wickramasinghe and Hoyle proposed that new flu strains are constantly raining down on the Earth from space. (They're not. They evolve here.) And in 2003 they proposed a similar theory about SARS, stating that it was so different from other viruses on Earth that it must 'logically' be extraterrestrial. (It isn't. It evolved here.) And the team repeatedly claims that the microbes they find in the atmosphere are aliens, or even that the rocks they've found are meteorites, while experts in the fields of astronomy, biology, and geology repeatedly dismiss their claims.

So if they aren't coming from space, how do microbes get up there? Updrafts are common movements that bring air from close to the ground to great heights, and small particles like bacteria, dust, and fungi easily get swept up with them. The particles are kept aloft by the continual winds in the stratosphere and the troposphere, which can range from about 22 miles per hour to almost 90 miles per hour. Also, while Earth's volcanoes aren't powerful enough to launch anything into space, they can certainly launch ash into the atmosphere, and microbes can be swept up too.

[Musical tone]

Izzie: Regardless of whether terrestrial fungi (or bacteria) originally came from outer space, they might have headed into space from Earth! We know that bacteria can grow and thrive deep within rocks, and of course fungi can also penetrate solid rocks with their hungry hyphae. So if a few billion hunks of Earth rock harboring life got smashed into space, it's fairly likely that some microscopic life does exist in the cosmos.

[Music begins]

Izzie: A Dr. Melosh wrote to Nature in 1988 that every crater on Earth greater than 62 miles across would have kicked "millions of tons" of rock from the Earth's crust into space. The Chicxulub crater from the dinosaur extinction definitely qualifies, as do two craters from Canada, one from Russia, and one from South Africa, as well as many unconfirmed craters more than 120 miles across, from all over the world. Many of the expelled rocks might have been boulders big enough to shield microorganisms from the dangers of space. Natural panspermia may have been happening for millions, or even billions, of years, with Earth unknowingly at the center of a ring of spacefaring microbes! And if microbes haven't hitched a ride off Earth yet, they probably will soon.

[Music ends]

Izzie: Research on the ISS has indicated that microbes are fairly space-resistant, and that's really important because our ecosystems rely on fungi and bacteria to break down waste and recycle materials. That could be extremely important if we ever decide to really try extended space missions, or colonize other planets or moons. Plus, mushrooms are yummy, and could be a great source of protein that doesn't take up as much space or as many resources as animals.

In a 2016 study, Drs. Venkateswaran and Wang sent eight species of fungi isolated from Chernobyl to the ISS for two weeks. They discovered several differences in the metabolism of the spacefaring fungi, identifying genes that are 'switched on' in fungi that are subjected to microgravity. They are also researching the genes and compounds fungi use to protect themselves from extreme radiation, hoping those compounds can be turned into a kind of "sun block" drug for human astronauts. But since those fungi are so good at avoiding radiation damage, they are also possible contaminants on space stations or colonies. And if those colonies also have people living in them, NASA or SpaceX or whoever will have to deal with all the fungi that live on human skin, in our guts, et cetera.

Speaking of contaminants, let's go back to Curiosity and the dirty drill bit – or rather, the not 100% clean drill bit. NASA does a super thorough job of trying to make sure that no Earth organisms make it onto the probes that they launch into space. But pre-launch sterilization can only get us so far. During launch, each stage of a rocket is unavoidably exposed to the microbes in the atmosphere. Still, treating Earth life as major contaminants is a good way to at least significantly reduce the amount of contamination we're sending out. Scott Hubbard, NASA's Mars Program Director, says that Mars samples will need to be treated the same way if they're ever brought back here. Until demonstrated to be sterile, they must be considered possible contaminants. After all, we don't want a real War of the Worlds!

Still, despite all our best efforts, any spacefaring object that passes through an atmosphere is probably going to have a ton of microbes on it. In part of his "What If?" blog series, Randall Munroe has calculated that if you assume that space bacteria studies are accurate, so 30% of the surviving bacteria on probes die every six years, there may still be 10 million viable bacterial spores on Voyager – fifty years after its launch! Since bacteria can reproduce asexually, it really only takes one stray endospore to seed out new life… and new civilizations.

[Slow theme music begins]

Izzie: So there we have it. Whether life evolves independently all over the universe or just gets passed from planet to planet, whether it moves along by random rock impact or on purpose for a colony's use, bacteria and fungi seem to be well adapted to space travel. It's possible, or even probable, that Earth life wasn't the first. And considering our departed dinosaurs and our remarkable rovers, Earth life also isn't the last. Bacteria and fungi are paving the way to the stars. Live long and prosper, little friends.

Morel Dilemma is written and produced by me, Izzie Gall. Our theme song is Fungi Among I, written and performed by John Bradley, and additional music is by Mihai Sorohan. You can find more of Mihai's music at mihaisorohan.bandcamp.com.

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[Music ends]

Resources

Amos, Jonathan. "Dinosaur asteroid hit 'worst possible place'." *BBC News*, BBC, 15 May 2017. http://www.bbc.com/news/science-environment-39922998

Black, Richard. "SARS 'from the stars'", *BBC News*, BBC, 23 May 2003. http://news.bbc.co.uk/2/hi/science/nature/2931246.stm

David, Leonard. "NASA's Mars Rover Curiosity Had Planetary Protection Slip-Up." *Space.com,* Purch, 30 Nov 2011. http://www.space.com/13783-nasa-msl-curiosity-mars-rover-planetary-protection.html

Dipe, F. "Why Having A Liquid Nitrogen Pool Party Is A Bad Idea." *Popular Science*, Bonnier Corporation, 20 Jun 2013. http://www.popsci.com/science/article/2013-06/why-having-liquid-nitrogen-pool-party-bad-idea

Dunford, Bill. "Europa: In Depth." *Solar System Exploration*, NASA, 2017. https://solarsystem.nasa.gov/planets/europa/indepth

Ghose, T. "Storm Clouds Crawling with Bacteria." *Livescience.com,* Purch, 23 Jan 2013. http://www.livescience.com/26533-loads-of-bacteria-hiding-out-in-storm-clouds.html

"Habitable Exoplanets Catalog." *Planetary Habitability Laboratory*, University of Puerto Rico at Arecibo, 2017. Accessed 11 May 2017. http://phl.upr.edu/projects/habitable-exoplanets-catalog

Hasegan, Dumitru; Mogildea, Marian; Mogildea, George. "Growth and Survival of Colored Fungi in Space (CFS-A)". *ISS Science for Everyone*, NASA, 7 Dec 2016. https://www.nasa.gov/mission_pages/station/research/experiments/636.html

Hawking, Stephen. "Aliens." Into the Universe With Stephen Hawking. Created by Darlow Smithson Productions, performance by Stephen Hawking and Benedict Cumberbatch, season 1, episode 1, Discovery Channel 2010.

Horneck, G., Bucher, H., Reitz, H. "Long-term survival of bacterial spores in space." *Advances in Space Research,* vol. 14, no. 10, Oct 1994, pp. 41-45. https://doi.org/10.1016/0273-1177(94)90448-0.

Knapton, S. "Oldest fossil ever found on Earth shows organisms thrived 4.2bn years ago". *Science*, 2 March 2017. Retrieved from http://www.telegraph.co.uk/science/2017/03/01/oldest-fossil-ever-found-earth-shows-alien-life-mars-likely/

Klyce, Brig. "Influenza from Space?" *Panspermia.org*. Astrobiology Research Trust. 26 Jan 2000.

Kvenvolden, K.A.; Lawless, J.; Ponnamperuma, C. "Nonprotein amino acids in the Murchison meteorite." *Proceedings of the National Academy of Sciences of the United States of America,* National Academy of Sciences, vol. 68, no. 2, 1971, pp. 486-90. Abstract. Retrieved from http://chemport.cas.org/

"List of impact craters on Earth." *Wikipedia*. Wikipedia, The Free Encyclopedia. 1 August 2017. Accessed 19 August 2017.

Love, Shayla. "What Radiation-Resistant Space Fungus Can Do for Drug Discovery." *Scientific American*, 11 Oct 2016. https://www.scientificamerican.com/article/what-radiation-resistant-space-fungus-can-do-for-drug-discovery/?WT.mc_id=SA_TW_HLTH_NEWS

Lovering, John. "The Murchison Meteorite Story." *Dynamic Earth*, Melbourne Museum. Retrieved from https://museumsvictoria.com.au/website/melbournemuseum/discoverycentre/dynamic-earth/videos/the-murchison-meteorite-story/index.html

Melosh, H.J. "The rocky road to panspermia." *Scientific Correspondence*, Nature, vol. 332, no. 21, April 1988, pp. 687–688.

Modica, G. D., Nehrkorn, T., & Myers, T. "An investigation of stratospheric winds in support of the high altitude airship P2.5," Preprints, 13th Conf. on Aviation Range and Aerospace

Meteorology, *American Meteorological Society*, 22 Jan 2008. https://ams.confex.com/ams/pdfpapers/128256.pdf

Munroe, Randall. "Distant Death." *What If?,* XKCD, 23 Oct 2014. https://what-if.xkcd.com/117/

Nicholson, Wayne L. et al. "Resistance of Bacillus Endospores to Extreme Terrestrial and Extraterrestrial Environments." *Microbiology and Molecular Biology Reviews*, vol. 64, no. 3, 2000, pp. 548–572.

"Our Work". SETI Institute. 2017. https://www.seti.org/node/647

"Panspermia and the Origin of Life on Earth." Panspermia-Theory.com. 2016. Web. http://www.panspermia-theory.com/featured/panspermia-and-the-origin-of-life-on-earth

Plait, Phil. "Followup thoughts on the meteorite fossils." *Bad Astronomy*, Slate, 7 Mar 2011. Web.

Plait, Phil. "No, Diatoms Have Not Been Found in a Meteorite." *Bad Astronomy,* Slate, 15 Jan 2013. Web.

Plait, Phil. "UPDATE: No, Life Has Still Not Been Found in a Meteorite." *Bad Astronomy*, Slate, 11 Mar 2013. http://www.slate.com/blogs/bad_astronomy/2013/03/11/meteorite_life_claims_of_fossils_in_a_meteorite_are_still_wrong.html

Plait, Phil. "Has Alien Life Been Found in Earth's Atmosphere? I'm Gonna Go With 'No.'" *Bad Astronomy*, Slate, 20 Sept 2013. http://www.slate.com/blogs/bad_astronomy/2013/09/20/et_claims_of_alien_life_in_earth_s_atmosphere_are_unfounded.html

Schmidt, Charles W. "The chemistry of life on Mars." *Chemical Innovation,* vol. 31, no. 5, May 2001, pp 12-16. http://pubs.acs.org/subscribe/archive/ci/31/i05/html/05schmidt.html

Shivaji, S., Chaturvedi, P., et al. "Janibacter hoylei sp. nov., Bacillus isronensis sp. nov. and Bacillus aryabhattai sp. nov., isolated from cryotubes used for collecting air from the upper atmosphere." International Journal of Systematic and Evolutionary Microbiology (2009), 59, 2977–2986. http://www.microbiologyresearch.org/docserver/fulltext/ijsem/59/12/2977.pdf?expires=1493080651&id=id&accname=guest&checksum=40ABD2CFFEE93431FB2E8F9A9C999C57

Shostak, Seth. "Are You a Martian?" The Blog. Huffington Post. 19 Aug 2015. Updated 19 Aug 2016. http://www.huffingtonpost.com/seth-shostak/are-you-a-martian_b_8010880.html

"The Meteorite." *Lunar and Planetary Institute,* USRA, 2017. http://www.lpi.usra.edu/lpi/meteorites/The_Meteorite.shtml

Treiman, Allan. "Fossil Life in ALH 84001?". *Lunar and Planetary Institute*, USRA, 2017. http://www.lpi.usra.edu/lpi/meteorites/life.html.

Wainwright, M. "Panspermia Life In Space." Milton Wainwright.com. 2015. http://miltonwainwright.com/panspermia-life-in-space/

Walbaum, Jonathan. "10 Facts About The Atacama Desert." Quasar Expeditions, 2017. Retrieved from https://www.quasarex.com/blog/10-facts-atacama-desert.

Wall, Mike. "New Alien Life Claim Far from Convincing, Scientists Say." *Space.com,* Purch, 20 September 2013.

Zhao, M., Bada, J.L. "Extraterrestrial amino acids in Cretaceous/Tertiary boundary sediments at Stevns Klint, Denmark." *Nature,* vol. 339, 8 Jun 1989, pp. 463 – 465. doi:10.1038/339463a0.