VENUS REVEALED: A New Look Below the Clouds of Our Mysterious Twin Planet
David Grinspoon, Basic Books, 1997.

Chapter 6
LIFE ON VENUS: A BARREN WORLD?

"The totality of life is merely a fancy kind of rust, afflicting the surfaces of certain lukewarm, minor planets"

--H.J. Muller

"It is with difficulty that we begin to grasp the mechanism of this transformation of solar energy into terrestrial forces. Its phenomena, which we are accustomed to regard from another standpoint, deceives us by the infinite variety of color, form and movement which are inherent in nature and of which we ourselves, through our life, form an integral part."

--Vladimir Vernadsky The Biosphere, 1926

"Cause you never can tell
What goes on down below.
This pool might be bigger
Than you or I know!" --Dr. Seuss, McElligot's Pool

"The universe is not only queerer than we imagine, but it is queerer than we can imagine"

--J.B.S. Haldane

NEW WAYS OF LOOKING AT LIFE

Is there life on Venus? Could there be life on Venus? The standard answers are "No and NO!". Venus is usually dismissed in a paragraph or two before an extensive discussion of the prospects for life on Mars, the icy moons Europa and Titan, and Earth-like planets elsewhere in the universe. Where life is concerned, Venus is consistently voted "least likely to succeed". In my opinion, this quick dismissal is not justified. It presupposes knowledge of the universal nature of life and the general characteristics of inhabited planets; knowledge that we do not yet possess.

Life is usually assumed to require organic molecules [1]dissolved in liquid water. Discussions of the habitability of other places in the universe have focused almost exclusively on the likelihood of finding planets with climate and atmospheric conditions that are "just right" for us.

By this standard model, Venus is obviously sterile because it is too hot and dry. But I think it may be premature to declare Venus off limits to life. I know that some may find this viewpoint ridiculous or even irresponsible. It could get me in hot water with some of my colleagues, but that's OK. Hot water, as a symbol for domains that are off-limits to life, is a very appropriate metaphor here.[2] In our present state of ignorance we should avoid all dogma in exobiology (the study of possible life beyond Earth).

Part of the problem is that it's difficult to define life, so how do we go about looking for it on other planets? Life is like a standing wave in a swiftly flowing stream - a stable structure through which matter and energy flow. If we are going to look for it around the universe, however, we need a more specific definition. Usually we define it as something like "a self-propagating chemical system that adapts to its environment." Two recent scientific movements suggest refinements to the definition, putting some new spin on our ideas about habitable places elsewhere. These two new developments are Complexity and Gaia.

I've already discussed Gaia in connection with life's possible role in Earth's evolution, but this perspective is also valuable for thinking about life elsewhere, and how we might recognize it. Gaia has its roots in the ideas of a remarkable Russian geochemist named Vladimir Vernadsky, who described the "biosphere" as that part of the Earth transformed by life. He defined life as a planetary property, as the way the Earth's surface responds to sunlight, covering itself with blue-green algae, forests, prairies and eventually parking lots and shopping malls.[3] "The Earth is literally covered with an uninterrupted film of living matter", Vernadsky wrote in 1926. He described how this zone of life had modified the planet, facilitating further development of life, and how life's participation in numerous geochemical cycles dominated the appearance, structure and chemical state of Earth's surface and atmosphere.

More recently the gaians have written of "geophysiology," describing mechanisms of self-regulation by which life may be actively controlling the climate and other conditions on Earth. Some of the details are still quite controversial. In particular, the extent to which life is really in control of Earth's overall environment is subject to continued debate. But the Gaia hypothesis has motivated a lot of good research into the intricacies of life's role on our planet.

It cannot be denied that life has fundamentally altered the appearance, atmosphere, climate and chemical composition of the Earth. Our world is awash in life. Interacting communities of organisms create one another's environments, and this "world wide web" shapes and is shaped by the Earth. In a very real and tangible way, then, the Earth -all of it - is

---

[1] complex molecules dominated by carbon.

[2] Or maybe it will just be given an icy reception. Equally appropriate.

[3] Fortunately for him, I don't think Vernadsky lived to see the advent of the modern mall. He died in 1945.

part of this circulating, self-perpetuating, complex, evolving, breathing, growing, dying, talking and dreaming thing called life.

The biosphere is a feature unique to our planet, so far as we know (which isn't very far at all). Life has a hold on the Earth and may never give it up, until the sun expands and consumes us five billion years from now. By then we may be long gone, watching the sun's dying pyrotechnics from a safe distance.

Life leaves its traces even in the "non-living" parts of Earth. Everywhere we find patches of chemical and physical complexity dropped by life in its haste. Life is so full of life that it occasionally spills it on the ground, leaving distinctive signatures of isotopes and chemicals, or structural patterns and rhythms for us to find. Should we find similar signatures and patterns on other inhabited worlds?

According to the Gaian view, life is a process that, once it gets started, becomes intimately involved in the later evolution of its home planet. Any inhabited planet should be brimming over with life, and life should have affected it physically in ways we might observe.

This overall concept has merit: but do we know enough to make specific predictions? The Gaians have made a nice first attempt to define the properties of inhabited planets. Their criteria, though, are of necessity heavily based on the example of Earth. They claim that we can tell whether a planet is inhabited from the composition of its atmosphere. Inhabited worlds have atmospheres that are out of equilibrium.[4] Equilibrium equals death. They note how Earth's lively, cycling atmosphere, far from equilibrium, is deeply related to the planet's capacity to support life and the effect that life has on the planet. This is contrasted with the "dead" worlds of Mars and Venus, which they portray as static, in equilibrium, with atmospheres that are "just sitting there." This may be true of Mars, but this view of Venus is outdated. Like Earth, Venus seems to possess lively chemical flows and cycles that may actively maintain the atmosphere and clouds.

One problem with the "disequilibrium" criterion for inhabited worlds is that it is vague. The atmosphere of Venus is definitely not in equilibrium. It is closer to equilibrium than Earth's, but how far from equilibrium must an atmosphere be before it is considered alive?

Another problem is that there are many nonbiological sources of atmospheric disequilibrium, such as lightning and ultraviolet radiation, even on the few planets we have studied. Furthermore, not all life creates chemical disequilibrium. On Earth, plants do, but animals do the opposite: they eat disequilibrium and excrete equilibrium. With every breath you take you inhale oxygen and exhale carbon dioxide, bringing the Earth's atmosphere a bit closer to an equilibrium state. Life giveth disequilibrium, and life takes disequilibrium away. So, do we really know what to look for? Shouldn't an atmosphere suspiciously close to equilibrium be just as likely to signify life?

In fact, the atmospheres of Venus and Mars are both "suspiciously" close to equilibrium. They are dominated by CO2, yet in their upper regions ultraviolet light naturally breaks up CO2, creating CO and O. Given this, atmospheric chemists have had some difficulty figuring out why the CO2 atmospheres of these planets are stable. We would expect both planets to have a lot more CO and O2 and less CO2. Is this a sign of life on these worlds? Are there creatures that

---

[4] See chapter 4 for a discussion of the meaning of equilibrium.

breath in CO and O2 and make CO2? Probably not. We think that we've found natural chemical pathways that reunite the broken CO2 molecules.

This example illustrates why is difficult to infer the presence of life from "strange" atmospheres. We don't know enough about non-biological or biological atmospheric processes to make sweeping statements. However, it's good that people are starting to think along the lines of a biosphere as something with planetary-scale properties. This helps us to think about what properties inhabited planets may have, and how they may differ from lifeless worlds.

COMPLEXITY: WHAT'S THE BIG IDEA?

"You got to stand and face it. Life is so complicated."
-- Ray Davies

"The truth is rarely pure, and never simple"
--Oscar Wilde

"Matter awoke and organized itself. The flame gave way to music".
--Hubert Reeves, Atoms of Silence

You've heard of the second law of thermodynamics: Entropy always increases. Things fall apart. If you don't keep cleaning your house it will become hopelessly messy. All the king's horses and men can't put Humpty Dumpty together again.

But how did Humpty get put together in the first place, if the universe always tends towards disorder? There are local tendencies towards increasing complexity and order which do not violate the second law, because it applies only to closed systems. If entropy (disorder) is lowered here, the universe pays for it somewhere else.[5] In our open system, Earth, life feeds off of the sun. It takes energy to make ordered structures like us.

Actually, it takes a flow of energy or matter to keep an engine, a life form, or a biosphere running. As we discussed in chapter three, flows always create differences, or gradients[6], a simple form of order. An engine or a life form feeds off a gradient in heat or chemical energy and always acts to reduce that difference. Without a continual input of new energy from outside, life forms and machines will erase all gradients, run down and die, producing a state of minimum order and maximum entropy where nothing changes. It can also described be described as a state of complete equilibrium. Pretty boring if you ask me.

The universe tends towards death and disorder. It's the law. But look out of any window or down at your toes. Our world is fantastically ordered and alive. Somehow, on the

---

[5] The total entropy of the solar system increases every day, mostly because the sun increases its entropy as it radiates energy.

[6] Recall the example of a gradient of salinity across the zone where rivers of fresh water flow into, and mix with, the salty sea.

surface of the Earth, the flow of solar energy is transformed into the fantastically complex ordered system of the biosphere. Why here?

In some circumstances, patterns seem to emerge spontaneously from the flow of energy. The effort to understand how order comes from chaos, has lead to the creation of a field called non-equilibrium thermodynamics. It was pioneered several decades ago by Nobel Laureate Ilya Prigogine, who coined the term dissipative structures to describe the forms that arise spontaneously in flows of matter and energy, dissipating energy and creating order along the way.

A simple dissipative structure, one we have seen many times in this book, is a convection cell, in which heat flowing through a system organizes itself into discrete patterns of upwelling and downwelling matter. This organization can be very simple or more complex. The weather patterns in planetary atmospheres are dissipative structures created by the flow of solar heat. The flow of heat out of planetary interiors also results in the spontaneous organization of convection cells. Whirlpools and tornadoes are dissipative structures, pockets of order created within energetic flows.

Non-equilibrium thermodynamics also helps explain how the fantastic complexity of life on Earth can have arisen in a universe that tends towards disorder. Convection cells are the simplest example of dissipative structures, organisms and biospheres the most complex. This tendency of matter to use flows of energy to form complex structures, in apparent local defiance of the universal second law, has also been called self-organization.

Have you heard any of the ruckus surrounding the new scientific field of complexity theory? It is the mathematical study of self-organization, a direct intellectual descendent of non-equilibrium thermodynamics, that was born with the advent of computers big and fast enough to simulate some of the complex processes in the real world.

The complexity theorists use computer simulations to mimic the emergence of order in natural systems, trying to develop an understanding of the principles governing the "emergent properties" that arise from matter in certain circumstances. I say "trying" because no one has yet developed an overall theory. But they have demonstrated intriguing similarities in the properties of many different kinds of complex emergent systems, including life-forms, ecosystems and societies.

We've all observed emergent properties. Sometimes a new behavior arises from interactions among the elements of a system - a new quality that resides more in the patterns of mutual interaction between the components than it does in the components themselves. One example is a phase change. When ice freezes or melts, the individual water molecules remain the same but their interactions change. Emergent properties can arise in groups of human beings, too. When a basketball team suddenly gets "momentum", it is something that happens to the team collectively and can't quite be explained by, or reduced to the actions of individual players. Suddenly their passes are connecting, they are hitting the basket. They are on fire, as a team.

The scientists involved in the complexity movement are attempting to arrive at a new way of describing the emergence of biological order. They see life as an emergent phenomenon that arose on Earth due to the right conditions, involving flows of matter and energy and the availability of chemical building blocks able to tap the potential for order. They may be laying the groundwork for a theory of life that does not depend on the details of conditions on Earth a "physics and math of evolution and metabolism."

Complexity does not threaten to replace Darwinian natural selection or render it obsolete, but it may augment it in ways that could throw new light on the marvel we call evolution. Darwinians speak of the "blind watchmaker" of evolution, which selects from completely random variations over long periods of time. The "mistakes" in the genetic code that enhance survival naturally tend to propagate themselves, and thus life slowly evolves. But some complexity theorists are now questioning whether the watchmaker is truly blind. They suggest that since nature seems to spontaneously seek order in some situations, this emergent behavior might be behind a lot of biological innovation. In their view, natural selection chooses from among a menu of spontaneously ordered options. Maybe the watchmaker of evolution is not completely blind, or is at least guided by some pattern-forming habits built into this universe.

That may explain why so many biological shapes are fractals. Fractals are forms with self-similarity across scale, that is, shapes in which the smaller parts are the same shape as the whole. Some examples are branching trees, spiraling sea-shells, and your nervous and circulatory systems. The most famous fractal of all is the Mandelbrot set. You know, those baroque, day-glo[7], Dr. Seuss-on-mushrooms designs you've seen on T-shirts and in music videos. These infinitely intricate patterns are all created from a simple mathematical equation, repeated over and over again on a fast computer.

The Mandelbrot Set and other computer generated fractals often seem remarkably familiar. You watch fractal videos and think "There's a sea-horse", or "there's a line of marching tigers". Why do the shapes of living things on Earth seem to have so much in common with these mathematically generated forms?[8] Fractals are a kind of geometrical complexity. Complexity theorists have found that many emergent self-organizing systems create fractal shapes.

Fractals are made by simple equations in iterative computer programs: the product of one round of calculation is used as the input for the next step. This is the mathematical equivalent of feedback, of a nonlinear process. Probably nature likes to make fractals because many natural growth processes are iterative. Somewhere their "instructions" contain the command "Go back to the previous step and repeat until done." For whatever reason, nature seems to love to assemble itself into fractals.

When you start looking for fractals on Earth, you see them everywhere. You see common geometrical forms in life from the micro to the macroscopic scales. The same shapes appear in life made from very different materials, on land and in the sea. Fractal forms seem to arise from basic physical constraints on growth processes, universal physical realities. Whatever

---

[7] There is nothing inherently colorful about these patterns. They are just collections of numbers being represented with an arbitrary color scheme.

[8] Some non-living natural processes make fractals, too, most notably erosive structures, like branching rivers. It is interesting that these forms usually involve some of the same conditions that make life arise, like flowing water. Is this a coincidence?

generates fractals may be deeply impeded in the rules of life, quite possibly deeply enough to transcend worlds. When we do finally meet the aliens, maybe they won't look completely unfamiliar! Anyone who has spent time looking at the Mandelbrot set might respond to the first pictures of alien life by saying, "Oh, I've seen THAT one before!"
[visual of part of mandlebrot set, Ernst Haekel drawing of micro-life, and Tory Read photo of fractal plant life at Botanical Gardens]

One possible answer to "what is life?" is "I don't know, but we'll know it when we see it." We might look for life on other worlds by examining photographs for well developed fractals. This search strategy assumes no particular biological mechanism, which is good given our ignorance and nature's inventiveness.

Of course there are geological forms, like branching rivers, that look fractal but are not necessarily related to life. Complexity theory would need to advance to the point where we can reliably predict which kinds of fractals are biological ones before we could make use of this strategy. Here is a prediction: We will find fractal forms, and they will seem familiar to us, when we find life on other worlds.[9]

Critics attack complexity theorists because they don't (yet) have a unified theory encompassing all the bits and pieces of this new research direction. They do, however, have a lot of intriguing results that are worth getting excited over, even if no one knows quite where it is all leading. Complexity represents a new way of looking at nature that doesn't quite fit the rules of science as it has been done. For example, it is inherently non-reductionist, focusing instead on emergence. One of the objections is that it is not predictive - at least not yet, in the way that science has required itself to be. Maybe in some sense it is not even science but natural philosophy. In any case, it is an important new way of looking at things that have traditionally been the domain of science. Complexity seems to be able to describe a surprisingly wide range of natural phenomena underneath one emerging branch of theory. We could miss out on something important if we dismiss it rhetorically because it provides no unified, predictive theory, or because it does not fit the old rules.

This dialog on the value of complexity is interesting to watch because it is a battle of cultures or even world-views within science. The debate is not just about whether certain theories are right, but about a way of looking at the world, and even the boundaries and definition of scientific thinking. To the extent that it's not science, science may reveal itself to be inadequate to deal with some territory that it has traditionally claimed. In this contest, I put my money on the "complexologists".[10]

Is life implicit in the laws of physics?[11] Does the universe have an inherent capacity or a tendency to become alive, given the right conditions? Many people have said that it does, that life has been in the universe from the word "bang." We have no way of saying for sure, at least

---

[9] I love this kind of prediction. I can only be proven right or wrong by a fantastic discovery.

[10] What do I win if I'm right?

[11] Some have said that complexity implies that we are "expected". I like "implicit" better than "expected", which implies that someone has been expecting us.

given what we know now. We can poke around the edges of this question with science, but it is also fair game for intuition and faith. I feel fairly certain that the universe wants to be alive, that the arrival of consciousness here, and probably elsewhere, is inevitable. We are the universe waking up. I do not have any strictly scientific arguments to support this, but everything I know and have seen of this universe, informed and enriched by all my scientific studies, as well as direct experience, contributes to this viewpoint. I prefer not to believe that we are the only conduits for consciousness in the entire universe, not because I have any evidence to the contrary, but because the notion seems absurd to me. Its largely a matter of aesthetic preference.   One of the exciting implications, for me, about complexity theory is that it may represent the beginnings of a quantitative theory that could address this question.

The current paradigm of exobiology has been around for about 30 years or so: life is carbon based, made by chemical evolution of organics in water. Earth-like environments are the only places where life can really be expected to flourish. You have to wonder, though, about any theory that concludes that our kind of life is the only kind, and that our planet is uniquely qualified to become alive. If complexity theorists can develop a general theory of living systems, maybe we will have criteria less dependent on our experience within the biology of only one world.

Perhaps a combination of ideas from Gaia theory and Complexity theory can help us to think more generally about planets as environments for life. Gaia encourages us to think of a biosphere as a global property that certain planets might possess. Complexity suggests that life emerges spontaneously amidst the right kinds energy and matter flow, and where conditions are suitable for stable structures to form and last long enough to perpetuate themselves.

What would make one planet better than another as a place for a biosphere to grow? Before we plant a garden, we till the soil, turning it over to ensure that nutrients are brought up from below and air is mixed in from above. A planet like Earth tills its own soil, with its constantly cycling interior, surface and atmosphere. This activity keeps nutrients and energy sources constantly available, making the surface of Earth a fertile place, a good niche for life. Planets like this may be likely to form biospheres as a natural consequence of their physical evolution. Perhaps an active, overturning surface, and an atmosphere with dynamic chemical cycles will prove to be good qualities for living worlds.

Even if you removed life, Earth might still seem like a living system, with its complex interweaving feedback cycles of matter and energy and many chemical reservoirs interacting and regulating each other on different timescales. Living beings are constantly renewing themselves, and living planets may do the same. Our skin seems permanent, but no cell lasts more than 2 weeks. Our bones seem solid but are always being deposited and re-absorbed, like an active planetary surface. So, just maybe, this is what's really required for life. Maybe a planet that is geologically "alive" is more likely to be biologically alive. Maybe, a living planet will always "look alive", in the sense that the Earth does, with a constantly self-renewing surface and atmosphere.

Venus has an active surface and interior and a lively atmosphere with complex chemical cycles that perpetuate gradients of matter and energy. In theory, this kind of disequilibrium environment could feed a steady supply of nutrients and energy to any creatures crafty enough to evolve in the Venusian environment.

Of course there is a serious objection to this. Neither organic (carbon) compounds nor liquid water can exist at the temperature of the Venusian surface. But how sure can we be that this rules out life?

LOVE THAT DIRTY WATER

"The universe is not only queerer than we imagine, but it is queerer than we can imagine"
--J.B.S. Haldane

First let me say that I am a big fan of carbon-based life. Some of my best friends are carbon-based. Carbon and water are two substances that each have incredible properties on their own. In combination they do something completely different, something that neither could do on its own. Carbon, with some oxygen, nitrogen and a few other elements mixed in serves as the universal template, the flexible yet solid Lego blocks of life that can build up an endless variety of huge and complex molecules. Water is the universal solvent. Dissolved in water, carbon molecules are free to flop around, twist themselves into complex shapes and interact with one another in the intricate dance that we call life. Something magical and creative beyond belief happened here as a result of carbon and water. Once it started it never stopped and it completely re-made our world. Carbon in water crawls and flies, respirates and synthesizes, colonizes, adapts, seeks and hides, gives birth, invents, worries, wonders and sings. If that's not magic, then what is?

Furthermore carbon-based life may be common in our universe. Both carbon and water are abundant everywhere we look, even out to distant galaxies. We have found carbon molecules, often mixed with water ice in comets, asteroids, meteorites, and even interstellar dust. Experiments have shown that at least the preliminary chemical steps of life might be commonplace wherever carbon and water meet. By contrast, the prospects for other kinds of life are dim- or at least uncertain. Or such is the view from here. - from this planet, so shaped by our kind of life, and also from inside our carbon based brains as we look out through our carbon-based eyes.

Science strives for objectivity and uses controlled, blind and repeatable experiments to remove the bias of the investigator. However, in the study of life we are the phenomenon under investigation. This makes objectivity difficult or impossible. Thus we should be very humble in our conclusions. Arrogance and dogma, in particular in an area where objectivity is impossible, are the antithesis of science.[12]

Sometimes I wonder if we are capable of thinking objectively about carbon-in-water. Are we deeply carbon biased? Who can blame us if we are? (maybe a sulfuric slime-sloth could.) I am talking about a possible bias to our perceptions here which is definitely not "subconscious" in the normal sense of the word, because that implies that it is based on some ideas that reside somewhere in the mind. This bias may be built into the chemical structure of our every cell. Pre-conscious might be a better word.

Our doors of perception are made of carbon-in-water. We see the universe through carbon-tinted glasses. Our very mechanisms of thinking and seeing are constructed of these same materials. Our external and internal worlds have been shaped by four billion years of carbon evolution. Much of what we are used to sensing and we find interesting is defined by this chemistry. This is pure speculation, but maybe carbon determines the patterns we respond to, and the scales of structure and organization that we notice. Not just spatial scales, but temporal ones: we are tuned to phenomena that change at the pace of carbon chemistry. Are we missing anything as a result? True, our science has been steadily increasing the temporal and spatial range of our awareness, opening up the filters. But the filters are there. These are some of the carbon biases which I can imagine. Some of them probably don't apply at all. But what of the biases which we can't imagine?

How much does this limit, or define, what we see of the universe? Is our love of carbon (and our propensity to view the universe's potential fertility wholly in terms of carbon-based life) merely a bias based on our local experience, or is carbon really the only way to live? I have no idea. It's possible that this is inherently difficult for us to know. We have here an example of one world with life. That is not much to base a solid scientific conclusion on.

For another angle on this subject, consider the phenomenon of path dependence. Certain choices made in the past, possibly at random, become entrenched as the machinery evolves to facilitate and use an existing system. A great example is the QWERTY keyboard found on every computer.[13] This layout doesn't make any sense for ease of typing. It came about due to the mechanical requirements of early "typewriter" design. Schemes to make typing easier have never gotten off the ground because this system is locked in: the cost of switching over is too high. You would have to change people's habits, change all keyboard manufacturing equipment, other equipment and software that interfaces with keyboard-driven machines, all the equipment used to manufacture that equipment and so forth.

Many of the specifics of our biological systems are path dependent. DNA is surely not the only molecule that living things could use to reproduce. Our protein-making machinery

---

[12] Such arrogance certainly will not win science many fans. Scientists often complain about the proliferation of pseudoscience, mysticism and superstition and decry the lack of faith in the scientific method. If we added more humility, and appreciation of the unknown and unknowable to our scientific education it could go a long way towards helping us compete in the world-view marketplace.

[13] This has its origins in an antique machine called the "typewriter".

uses only 20 of the many possible amino acids. There is no obvious reason why these twenty are the best, but the system was perfected using these long ago. One feature of such a path-dependent evolution is that a system that has evolved to the point where it operates well, with efficiency and reliability, may seem like the best (or only) system even if it is only one of many possibilities, dependent on arbitrary choices made long ago which have since been codified and maximized.

It is obvious that this could be the case with some of the specifics of our finely tuned biochemistry. But how deep does this path-dependence go? Is it possible that some of the more basic choices our biochemistry has made, like the choice to go with carbon and water, could actually be path dependent? If we had started out with a different system, would it by now have evolved to the point where it works so well that it seems to us like the only one possible? "Geosphysiology" suggests that biological evolution always reworks its planet to optimize it for a growing biosphere. Maybe any sufficiently evolved chemical system will appear, to organisms evolved within it, as the only possible kind of biochemistry, at least when they first wake to consciousness and assess their situation in the cosmos.[14]

Carbon may need very special circumstances to come alive. In a wide range of conditions and locations carbon spontaneously forms the small modular units, like amino acids, that could be the building blocks of our kind of life. In the right conditions these units can assemble themselves into the large, complex organic molecules of "life as we know it". (like proteins, which are long chains made of thousands of amino acids) But, those "right conditions" define a much more narrow set of requirements. Carbon probably needs liquid water. It probably also needs a certain pH range (neither too acidic nor too basic), and some protection from the ultraviolet radiation which is ubiquitous in the universe. Most places carbon does not have "the right stuff", does not behave in such a way as to be conducive to life. As far as we know it's only in the unique liquid water environment of the Earth that these little bits of carbon get together and make life. This is why our thoughts about searching for life on other worlds are so focused on looking for other planets with liquid water.

If we lived in another environment, would carbon seem so special to us? If we lived on Venus, we might not even know about organic chemistry. Carbon would be something that exists as an oxidized gas (CO or CO_2) at room temperature and does not form stable complex molecules. Maybe we would learn about carbon molecules in the interstellar medium, on comets, or on Earth. Maybe we would notice a pervasive green pigment on Earth that seems to involve carbon chemistry. We might call it the "unknown absorber".

The temperature range of liquid water informs our intuitive sense of what is too hot, what is too cold, and what is just right for life. The properties of complex chemicals like proteins and DNA are highly sensitive to their external environment. That is why "life as we know it" has such a narrow comfort range. Heat us up just a bit and we cook; our proteins "denature", falling apart into their constituent amino acids. Cool us down a bit too much and we freeze, our cells turning to ice crystals that shred our cell walls. The realm of water defines

[14] Is it possible that our expectation of finding life that is chemically just like us, on a planet similar to ours will seem, from some future vantage point, as quaintly naive and amusing as Star Trek aliens who all look like humans with minor anti-cosmetic surgery?

terrestrial life's ultimate boundaries. Is it the same in the universe at large? Does life always need a watering hole?

Or does the universe have other ways to solve this problem? Could it be that by only seriously considering carbon-based life we are blinding ourselves to much of the universe's true biological potential?

One of the lessons we are learning from our recent explorations of Venus is that nature is not likely to do exactly the same thing twice in the evolution of complex planets. Could it be the same with the evolution of complex life?

LIFE OUTSIDE THE KEY OF C?

An obvious objection to this line of argument is the following: we have not thought of any other ways to do it. If there are other possible biochemistries, then what are they? Make a countersuggestion! I am not persuaded by this objection. It's true that no one has devised an alternative biochemistry, but this could be a measure of our ignorance. I think it is safe to say that we would not have thought of carbon-based life either, if we hadn't had the Earth's example to examine and dissect.

We are still trying to learn how biochemistry works here on Earth. We do not know nearly enough to have figured it all out from the basic laws of physics and chemistry. It's no accident that chemistry is a metaphor for unpredictable human interactions: in the same way, we don't know nearly enough to be able to predict what the outcome of all possible chemical combinations will be, although we are getting better at it in some cases. If we ever did perfect this art (or science) there would be no need for experimental chemistry.

We are still clueless about many details of the workings of our own bodies, but we know carbon chemistry fairly well because we are naturally curious about it, and there are huge economic incentives to study it. What other element can claim to be the basis of several academic disciplines (organic chemistry, biochemistry) and numerous multinational corporations (Sandoz, Genentech)? Who knows what potential, what lurking complexity, what surprises we would find if we turned the macroscope of our intellect with such sustained and focused intensity on any other corner of the periodic table?

These days many people are trying to save Earth's rain forests from destruction. This is important not only because of their role as a contributor to the global atmospheric balance and a habitat for life, and not just because of their sheer priceless beauty, but also because of the vast and largely untapped chemical creativity in the forest species. We are still finding substances with significant pharmaceutical potential that we haven't the foggiest how to invent or manufacture. Time and again, even in the familiar environs of Earth, we find that "dumb" nature is so much smarter and more resourceful than we are. How can we put narrow limits on its creativity elsewhere in the universe? Nature always surprises us. Why shouldn't this be true on the level of planetary environments and chemistry for life? If the universe wants to be alive badly enough, it will find a way. Nature will find the hidden pockets of order, nurture them, and shape them into biospheres which grow into and with their worlds, transforming them into magic kingdoms like, but unlike, our own. To assume that carbon-in-water life is the only kind possible could be like our historical assumption that Earth was the only world.

LOOKING FOR LIFE UNDER THE STREET LIGHT

"They are ill discoverers that think there is no land,
when they can see nothing but sea."

--Francis Bacon

At a conference I attended recently, a colleague began his talk on exobiology by stating, "We assume that life requires liquid water because otherwise the problem is completely unconstrained." He went on to give a brilliant talk on the prospects for finding habitable planets. Using carbon-in-water life as a frame for our research efforts we have done some very good science. We determine the effects of the distances of planets from their stars and define a "habitable zone" within which life could flourish. Then we estimate the number of planets in our galaxy that may reside within these zones, and could support life. There is no way to test these ideas until we find some more Earth-like planets, but this work helps us see the Earth in a wider context, and it is useful for gauging the prospects of water-based life in systems of planets around various types of star. NASA's plans for future initiatives to find other life in the universe also focus on searching for Earth-like planets and atmospheres.

If you lose your car-keys at night on a long, dark street, where should you look for them? There is a joke about looking under the street light because they would be easier to spot. This may seem like a silly strategy, but actually it makes a lot of sense to start searching there. Since they could be anywhere, why not look first in the stretch that is well illuminated? You may get lucky and find them there. But, you should not have the misconception that they are actually more likely to be under the light. And if you don't soon find them, you will need to venture out into the darkness.

If we want to search for life on other planets, then looking for liquid water is a very practical starting point. We need "well-posed" questions to study, something concrete to work on. We can't (yet) really do science to address general questions like "what is life", "what forms might it take?", "what kinds of environments does it require?", and "How would we recognize it"? We need specific theories to test so we can make predictions, do experiments, and evaluate the results. So we focus our research efforts on more specific questions like "Is there carbon based life, similar to ours, on other planets?" and "How common might such planets be?". These questions are well illuminated by our knowledge of terrestrial biology. By investigating them we can use the power of science to chip away at the larger questions. We should certainly continue along these lines, but we should also remember that our search criterion are limited by pragmatic concerns, not by real knowledge of life's limits. This limitation winds up contributing to an air of confident consensus about the best places for life to evolve. We are looking under the street light with these efforts, but we usually don't present it this way.

The question of life elsewhere is a huge domain of unknown territory, a long darkened street. We poke around the small areas in the light, which we can investigate with well-posed scientific questions while we await a more general theory of life, one that will provide more general search criteria and allow a scientific search for life in the darkened corners of the universe. Yet we are impatient to start our search, because we want to know if we are really alone. There is nothing wrong with beginning to look, as long as we acknowledge that we don't completely know what we are looking for.

But, should we stop at the edge of the light? Whether or not our search for nearby water-borne life is successful, eventually we may want to venture out into the darkness of more unfamiliar chemistry and relatively unexplored thermodynamic spaces.

But how would we go about this? We cannot investigate in detail every possible kind of chemistry in every conceivable environment. Such a research program would be hard to fund, unlikely to yield anything useful in any given day or year, and possibly quite boring to do. But nature is conducting these experiments somewhere, and has been doing so all over the universe for a long time. Who knows whats been cooked up?

Is there a less geocentric, less parochial, set of criteria for detecting extraterrestrial life? Unfortunately, we don't have anything like this, at least not yet. In the meantime, another approach might be, instead of looking for very specific chemical signs, to look for unexplained complex phenomena. Perhaps we should take a more general approach, being on the lookout for signs of the unusual and the seemingly improbable. In my view, we should regard any mysterious phenomenon of global scale, especially those that involve unusual states of chemical disequilibrium or equilibrium as possible signs of life. We might also look for globally pervasive unexplained absorption signatures, which could be photosynthetic pigments of some kind. Since we have no precise criteria for this quest, we must cast a wide net, or we could miss something.[15] With a great degree of skepticism, but also a healthy appreciation of our grand ignorance, we should regard these kinds of features as unlikely, but possible, biological phenomena, until we find other satisfactory explanations.

LIFE ON VENUS: AN AGNOSTIC VIEW

Every age of science is so sure of itself, sure that it has almost all of the answers. In hindsight, centuries later, we often find we were far off the mark. We cannot say which conceits of the science of our day will seem hubristic and narrow to those of later ages. If I had to hazard a guess (and this is hazardous!), I would name two: One is the idea that we have almost figured out the whole universe and need only one last equation, a "final theory" that will give us all there is to know. The second is the idea that all life must be made of the same stuff we are made of.

If we relax this criterion, then the ban against life on Venus is less certain. Everyone seems to be convinced that it is completely obvious there is no life there, but several new

[15] The so called "face on Mars" definitely does not fit these criteria, mostly because it is not mysterious. It is a rock formation that looks face-like only under certain lighting conditions, and has been used for commercial exploitation of the gullible. Another crater has a pretty good "happy face" in it. Does this mean that there was once a thriving "rave" culture on Mars? Be suspicious of all claims of extraterrestrial life detection.

developments have made me re-think this - some new ideas about Venus and some new ideas about life. Venus may have some of the general properties of a "living planet": a geologically active surface and a self-refreshing atmospheric and cloud system. Some scientists working on general theories about biological evolution believe there may be a tendency in the universe for self-organization, complexity and - just possibly - biology. This may or may not have specific chemical requirements.

Admittedly, this is a long shot, but I consider life on Venus to still be an open question. In any case, thinking about it is a worthwhile exercise that may help us to better understand the real limits of life.

This solar system is full of surprises. We keep finding familiar processes occurring in the strangest of places. Nobody expected to find "rivers" on the plains of Venus or "snow" on its high peaks. On Venus, sulfuric acid plays the role of forming clouds, just as carbon dioxide does on Mars and methane does on Titan. Other substances are condensing out on the mountain tops and sustaining long distance flows. These are all roles played by water on Earth.

Planetary evolution has certain recurring themes: phenomena and structures that are common on planets with widely different conditions. When the material that plays this role on Earth is unavailable or inappropriate, then something else takes its place. Different physical conditions allow different substances to step up to the plate and perform the same function. Could it be so with life?

In this view, the statement "Life can't exist on Venus because it's too hot." may be analogous to "It can't snow on Venus because it's too hot." If rivers can form on Venus without a drop of water, maybe some kind of cells and organisms could evolve, using stuff that we are not predisposed to think of in such a role. A living cell is much more complex than a river. Does that make it more or less likely that we would recognize or imagine the correct analogy?

FISH TALES

When I was little, one of my favorite books was McElligot's pool by Dr. Seuss. It is one of the good Doctor's early, lesser-known works, but I think it is an undiscovered gem. I used to make my mother read it to me over and over.[16] The book concerns a young dreamer named Marco who is ridiculed for fishing in McElligot's tiny, stagnant pool, a place where everyone knows he will never catch anything but old cans and boots. Marco answers his critics with an elaborate and imaginative fantasy. He thinks: "This MIGHT be a pool, like I've read of in books, connected to one of those underground brooks!" He imagines that this stream is connected to a subterranean river, and :"This might be a river, now mightn't it be, connecting McElligot's pool with the sea! Then maybe some fish might be swimming toward me! (If such a thing could be, They certainly would be!)" The rest of the book catalogs an incredible menagerie of exotic fishes out of Marco's (Dr. Seuss's) bountiful imagination, all of which might be parading towards his little pool to bite his hook at any moment.

---

[16] I mentioned this to her recently, probably close to 30 years after the last of these readings, and she flawlessly recited some lines from it.

Sometimes the logic we use to discuss extraterrestrial life reminds me of McElligot's Pool. Take the search for life on Mars:

Mars today is not a likely home for life as we know it. It is too cold and dry, and the surface is bathed in deadly ultraviolet radiation. And Mars is in many ways a dead world. There is little active geology, and little fluxing of energy and matter between reservoirs in the surface, atmosphere and interior.[17] These are the flows that on Earth establish gradients and niches in which life can build itself.

Yet one amazing discovery we've made about Mars has gotten us excited about the prospects for past (and just possibly current) life there. Orbital photos show that there has almost surely been running water, and probably standing water there in the past. This implies that Mars once had a warmer climate, which probably required a thicker atmosphere that would have protected the surface from deadly ultraviolet rays. In its early history, Mars may have been more like Earth, a place where carbon molecules could have found many a friendly watering hole to evolve into life.

Even though the environment has changed over the eons, become cold and dry, iced-over and irradiated, maybe life - if it got started there - has hung on somehow. This possibility prompted the Viking biology experiments we landed in 1976. We found some unusual chemistry in the soil of Mars, but we didn't find life. Viking also showed us that there are basically no organic molecules in the soil of Mars, as might be expected in an ultraviolet killing field.

These elaborate instruments tested the hypothesis that the surface of Mars is covered with Earth-style life. The results seem to be negative, but that has not stopped our search for life there. If you are attached to the idea of life on Mars, you can retreat to the positions that: 1) life might be isolated only in certain pockets of the surface, so any random landing site would be sterile; 2) there is life underground, just below the depth to which the landers sampled; 3) Mars might still have pockets of warm water, in hot springs, supporting colonies of life; 4) Life there is chemically very different and would not respond the way the designers of the Viking biology experiments expected; 5) Life may have evolved on a past Mars with a more Earth-like environment but died out when the climate changed, leaving fossils that we can find.

The naysayers might declare "You'll never find life on that scrawny little planet, with its deadly ultraviolet radiation, freezing temperatures, lack of organic chemicals, and poisonous atmosphere." We dreamers, though, see some dried up river beds and think: Just maybe these were carved by running water which might have been connected to a mighty ocean in the past. And that ocean just might have had organic molecules that behaved like Earth's, and just maybe a thriving biosphere evolved. And maybe even this life is still there hidden in underground caves or hot springs. Or, these signs of past water might lead us to fossils of past life. Faced with the logic of McElligot's pool, there is no way to disprove the existence of life on Mars. Anyone who wants to believe is free to do so, in no danger of violating any scientific principles.

---

[17] There are active seasonal cycles of condensing and sublimating CO_2 and H_2O, but these don't involve much chemistry.

I do not mean to ridicule the dreamers. I am firmly on the side of Marco and the believers in possible life on Mars. The argument for the possibility of fossils is especially compelling. Both Mars and Venus could have had similar environments to Earth when life was getting started here. It's possible that the same magic started up in the oceans of all three worlds. Mars, because it is geologically dead, has preserved its past (including any fossils) best. If this fish story seems unlikely, it is also worth considering how important and exciting success in such a search would be. And the effort is inherently worthwhile. Fishing is a good way to spend time even if you don't catch anything. The search for life, futile or not, can't help but teach us a lot about Mars and terrestrial planets in general. So, why not look?

Mars could have isolated pockets of hydrothermal systems, supporting underground bacterial colonies. But two ideas about life as a planetary phenomenon argue against this. If Vernadsky is right, life is a widespread property of a planet that covers it entirely if it exists at all. The signs of life will not be subtle; living planets will exuberantly announce themselves to the most casual observers. The terrestrial example, where life has tenaciously and aggressively expanded and colonized, finding toeholds almost anywhere you could imagine, certainly supports this view. If the "gaians" are right, then life should be obvious from a distance due to its effects on the atmosphere. These arguments seem plausible, but they are not completely compelling because we don't really know what life will do to a planet and what we should look for.

I've presented the Mars story in a way that draws attention to the importance we place on water. If our search continues to yield negative results, we will have to invent new possible hiding places for Martian bugs. But we cling to the signs of past water on Mars as a possible link to our own biochemistry.

If we relax, for a moment, our rule that life must cling to water, then the prospects for life among the terrestrial planets seem a bit different. As I discussed earlier, Mars is the most Earth-like of the other planets in its surface conditions, but Venus may be the most Earth-like in its activity. All three planets started out young and restless, with warm churning interiors and water flowing on their surfaces. But they've gone their separate ways. Mars cooled off, ceased its geological activity, and lost most of its atmosphere to space. Its water either left for space as well or else is hidden, probably frozen, underground. Mars today is a dead world, still wearing the surface scars of the solar system's violent birth.[18]

Venus too lost its ocean, but it retains an active, churning interior and a surface that has been re-worked many times by processes which are apparently still ongoing.[19] It has a non-equilibrium, chemically restless atmosphere and supports global clouds which function in some ways like Earth's oceans.

Again we must ask what life really wants and needs. If life follows water, then Earth may be the only living world in our solar system. Life could have started on all three worlds,

---

[18] By the way, if Mars is uninhabited, that makes it a better place for humans to settle. We don't have to worry about disturbing the inhabitants.

[19] As I've discussed, we don't know if Venus was born as wet as Earth, but it surely had some water to begin with.

and been banished from Venus and Mars as they lost their oceans. It could also conceivably be clinging to isolated watering holes beneath the surface of Mars.

If life needs an active planet, with continuous sources of energy and nutrients, and is less picky about its chemical choices than we have imagined, then Venus may be the best hope for other life nearby.

In case you haven't read too much about this subject, I should say that the opinion I am expressing here is not a popular one. The possibility of life on Mars is a common theme in the scientific literature, and you can frequently read about it in Time and Newsweek, too. Life on Venus is never discussed. Nevertheless, I think current life on Venus is at least as likely as current life on Mars.

STRANGE FRUIT

"There is no excellent beauty that hath not some strangeness in the proportion" -- Francis Bacon

Life needs a constant flow of nutrients. Chemically, it needs a suitable architecture and an energy source. On Earth the architecture is always based on carbon bonds but the energy sources have varied.   We have organisms that use many kinds of organic carbon compounds (personally, I like sugars), but there are also critters that derive their energy from sulfur, hydrogen, methane or even iron compounds. Recently we have discovered bacteria that live in caves deep underground, eating rock and breathing hydrogen. On Venus, energy sources are no problem, but what would the architecture be?

Since I have argued that it may be beyond our current abilities to imagine other possible biochemistries, I don't feel obligated to propose an alternative. But, just to advocate for the devil, or at least show him a little sympathy, let me bite the bullet and propose a chemical basis for life in Hell: How about sulfur, the stuff of brimstone, fool's gold and rotten eggs?   Maybe sulfur is the magic stuff on Venus, the way carbon is here. Sulfur is common on Venus, existing in a menagerie of molecules in the interior, on the surface and in the atmosphere and clouds. In its elemental state (bonded only to itself) it takes many poorly understood forms in every phase (gas, liquid, and solid). Sulfur reacts in interesting ways with carbon, oxygen, nitrogen, phosphorous, fluorine and chlorine, all common elements in the universe, all present on Venus. Even in our supreme state of ignorance about how sulfur may act and react in the conditions found on other planets, we do know that sulfur compounds can store large amounts of energy and make complex and unusual structures. In certain conditions sulfur forms polymers, the long chains of repeating structures that give carbon an edge in the life game.

Sulfur is everywhere on Venus, cycling through every reservoir, constantly changing form, absorbing and releasing energy, driving and riding the winds. The sulfur cycle on Venus is probably the closest extraterrestrial analog to the carbon cycle on Earth. Carbon passes through our biosphere, oceans, atmosphere, and interior, assuming a myriad of organic and inorganic forms, controlling our climate along the way. On Venus sulfur belches from volcanoes and reacts with surface minerals only to be buried in the mantle until it is again volcanically liberated; or it reacts with oxygen, carbon, and other elements in the atmosphere to form the molecules that dominate the chemistry and climate of the planet. Sulfur absorbs ultraviolet radiation in the upper atmosphere, providing an energy source for chemical reactions that make precursors for the global clouds. The clouds themselves are liquid droplets made of sulfuric acid with other substances dissolved within. Sulfur compounds are a leading candidate for the "unknown ultraviolet absorber" that controls the light-absorbing properties of the cloud tops and strongly affects the circulation of the clouds and upper atmosphere. Sulfur on Venus is alive, at least in the gaian sense in which portions of a planet resemble living systems in their complex feedback cycles. Whether it is alive in the more traditional sense of forming self-propagating organisms is anyone's guess. Most people would guess "No way!". I say, "Who knows?"[20]

There are some good arguments about how the chemical properties of carbon and water make them uniquely qualified to be alive. These involve the specific kinds of bonds that carbon atoms make and the distinctive physical qualities of water. I won't repeat these here, but I admit that I don't know how sulfur could do some of these things. I reiterate, however, that there is a lot we don't know about how the universe behaves. If self-organization is an inherent property of matter that expresses itself in certain environments, it may not be bothered by these objections.

LIFE SIGNS?

"Nothing is harder, yet nothing is more necessary than to speak of certain things whose existence is neither demonstrable nor probable. The very fact that serious and conscientious men treat them as existing things brings them a step closer to being born."

-- Herman Hesse, Magister Ludi

I have now crawled so far out on a limb that I see no reason to try climbing back. I may as well jump! So let me propose some possible signs of life on Venus. Let me state clearly that I regard each of these possibilities as extremely unlikely. But in the search for life the criteria for declaring a negative result are different than in, say, the search for volcanoes, since we don't really know what we are looking for.

Here are four phenomena that could be (but are almost surely not) signs of life on Venus:

---

[20] Brave researchers willing to test this hypothesis may have to go underground. We can imagine clandestine Venus Simulation Labs hidden in the woods, run by dedicated workers living in constant fear of being busted by the Carbon Squad.

1) The atmospheric "superrotation" could be created by life.

This is one of the most obvious and large scale unexplained features of the planet. The dark ultraviolet markings whip around Venus in swift and colossal winds, circling the planet every four days. No one has come up with a convincing explanation for this. A biological explanation would be really stretching things, but, from the point of view of any Venusian bugs that want to use sunlight for energy, the supperrotation would be a major plus because the night is so long there. The planet may rotate too slowly for photosynthesis unless you have something like a superrotation.

Perhaps Venusian organisms somehow use solar energy to create another kind of energy or mass flow, which is then transformed into mechanical energy to drive the winds. Radiation in the clouds might be absorbed by microbes suspended in the cloud particles, and the resulting temperature structure could cause biologically controlled winds to blow. In fact this mechanism, called "radiative dynamic feedback," has been invoked in less radical, non-biological form, to explain some of the observed structures in the clouds.

Picture the clouds as a kind of super-organism that absorbs light in such a way that it keeps itself spinning, and no part of it has to stay in the dark too long. It's pretty hard to imagine, but not too much harder to believe than any of the previously published attempts to explain the superrotation.

2) Maybe the "unknown ultraviolet absorber" is a photosynthetic pigment.

We love sunlight, but not all of it. We like the visual portion, which illuminates the surface of our world and fuels the life upon it. Shorter wavelength, ultraviolet light is lethal to us, because this higher energy radiation rips apart carbon bonds. Imagine creatures that have evolved some alternative chemistry to tap the huge amount of energy in the ultraviolet portion of the sun's spectrum. Maybe they think that no life could possibly be sustained by the lackluster, low-energy photons of visible radiation. Photosynthetic life on Earth makes use of chlorophyll, the ubiquitous green pigment. If Venusian life has evolved to take advantage of UV light, this might be done in the form of a pigment that absorbs ultraviolet. If this is some complex chemical unknown to us, that could explain why we have had such a tough time figuring out the identity of the "unknown ultraviolet absorber." In the context of the previous discussion of sulfur chemistry, it's interesting that the unknown absorber is closely associated with sulfur-containing gasses. It appears in bursts alongside gusts of SO_2, almost like algae blooms in nutrient-rich waters on Earth.

After the Galileo spacecraft flew by Venus, it made two close passes by Earth. These were great opportunities to observe our own planet from the vantage point of a spacecraft encounter. Much was made of how Galileo "detected life" on Earth. But of course we knew what we were looking for. One sign of life was the widespread global signature of chlorophyll, a strong absorber of radiation at specific visible wavelengths By the same standard, didn't Galileo "detect" life on Venus? Only in this case, the "pigment" absorbs in the ultraviolet and probably involves sulfur chemistry rather than carbon chemistry.

Going to another planet and saying "Why isn't it green?" is like going to another country and saying "Why do the people look and talk so funny?" The question is biased with an inappropriate extrapolation of one's limited experience. It's not easy being green. Chlorophyll works very well here, but we know nothing about its universal appeal, and common sense dictates that other planets with different histories and conditions would evolve different ways of harnessing solar energy in the service of complexity and life. We could generalize the question, and instead of "why not green?", ask "why is there no widespread efficient absorption feature of unknown origin?" But in the case of Venus, there is one: the unknown ultraviolet absorber. (Again, I want to reiterate that there is probably a non-biological explanation that we have just not stumbled upon yet.)

3) Maybe Mode 3 cloud particles are alive.

As I described in chapter 3, the clouds of Venus are humongous and very complex. They cover the planet, rising from a base about 30 miles above the ground to an altitude of 45 miles. They are stratified into three distinct layers, with relatively clear air in between. There are at least three separate populations of cloud particles, which we describe with the incredibly imaginative terms, from smallest to largest, Modes 1, 2 and 3.

Mode 3 particles are the odd ones. They range in size from 5 up to at least 35 microns. There have been a lot of contradictory measurements of their size, shape and composition, and we do not yet have a good description of them or explanation for them. They may not be spherical in shape: they may be solid crystals. Some measurements suggest that they are made of sulfuric acid, like modes 1 and 2, but there is also evidence of more exotic chemicals, like chlorine or nitrogen compounds. They might be sulfuric acid droplets surrounding some other substance, perhaps one that forms a solid core suspended in the interior. Could those strange cores be some kind of creatures?

An exobiologist friend of mine dismisses the idea of cloud life anywhere. He asks, if this is possible, then why aren't the clouds green on Earth? It's a good point. Life on Earth is opportunistic, inhabiting every niche it possibly can. If cloud-life were possible, Earth's clouds would presumably be full of it. This argument once again limits us to extrapolating from the known, which is generally a safe tactic in science. I am not convinced it is a good idea when thinking about exobiology.

After all, the clouds of Venus are a very different kind of place from the clouds of Earth. They are a much larger, more continuous, more stable environment. The difference in stability is important. Models indicate that cloud particles there last for several months, much longer than those on Earth. An enterprising species could easily fit its life cycle into those months, seeding other cloud particles with its progeny before falling into the hot winds below.

The clouds are where most solar energy is absorbed and the site of some of the greatest chemical and energetic flows on Venus. They are also full of interacting liquid droplets, which may have been important in the origin of life on Earth. And maybe in their own way, the clouds of Venus are "green." Green for Venusian life might be in the near-ultraviolet. This may be pushing things, but if I were devolved matter thinking of establishing a biological beachhead on Venus, I would take a good look at the clouds, the ocean of Venus.

It's also worth noting that the temperature up there is much milder than at the surface. In fact, conditions in the clouds of Venus are not too different from those at the surface of the Earth. There is a level in the clouds (about 33 miles up), where the atmospheric pressure is about 70% of the pressure at sea level on Earth, and the temperature is a balmy 107 degrees Fahrenheit. For ballooning at this altitude on Venus, you would need only a thin, acid resistant suit, an oxygen tank, and a large supply of cold lemonade. It's cool enough for liquid water, and small amounts of it exist there (in a strong sulfuric acid solution).

Still, something in my gut tells me that the clouds of Venus are not a good biological habitat. That something is stomach acid, hydrochloric acid. Acid eats organic molecules. The Venusian clouds could be a niche for "life as we know it", depending on carbon in water, if it weren't for all that damn acid. But we have recently discovered that there are thriving colonies of bacteria living in some people's stomachs, much to their discomfort (the people, not the bacteria). This is one example of the innumerable ways that we seem to be still learning, all the time, of surprising new niches where life can live on Earth. The crafty bugs in our guts have found a way to build an insulating lining protecting their innards from the acid environment. Who can say that Venusian bugs couldn't do the same? Earth life can adapt to a highly acidic environment. Still, the Venusian clouds are much more acidic than your stomach, unless you are having a REALLY bad day, but some bacteria on earth thrive even in concentrated sulfuric acid.

4) The highly reflective mountain tops could be covered with life.

Some kind of transformation happens to the ground all around the planet above an altitude of 13,000 feet (which corresponds to a temperature of 820 degrees). I have mentioned that this could be analogous to a snow-line. What about a "tree line"? I am not suggesting that the high peaks of Venus are forested with Douglas Firs, but it is certainly conceivable that this temperature boundary represents the edge of the "habitable zone" on Venus. Perhaps some non-carbon-based equivalent to lichen grows on Venusian rocks below a certain temperature, feeding off of the disequilibrium sulfur gasses. These creatures could be causing come chemical change in the ground which concentrates radar reflective materials.

With these four possibilities I don't mean to imply that life on Venus is deducible or probable given our present knowledge. But perhaps the intellectual exercise of considering such possibilities can help us to sharpen and expand our thoughts about the nature of life and how we might recognize it.

If we were to take any of these ideas seriously, how would we test them? Out of all of these wacky proposals, my favorite is the hypothesis that the "unknown ultraviolet absorber" is really a photosynthetic pigment. For starters, we could do some experiments simulating the environment of the upper clouds of Venus in laboratories on Earth and see what grows. However, funded exobiology research tends to be focused on water-based life, and on Mars, so I don't know if there would be any support for something like this, especially these days when even excellent and reasonable research proposals routinely get turned down for lack of funds.

If I were sending a mission to Venus to look for life, I would do two things. First I would capture lots of cloud particles, take pictures of them with microscopes, send the pictures home and see if they looked alive. This would not be expensive, because the whole apparatus could be tiny. Much of the cost of atmospheric entry probes is due to the size and weight of the pressure vessel required to protect delicate scientific instruments in the lower atmosphere. A dedicated mission to send a microscope with a camera into the clouds of Venus would not cost all that much. The only problem is in all likelihood it would return nothing much of interest. This is a problem with any mission to test an exobiological hypothesis. Most of them will be far-fetched and most of them will be wrong. But if one ever turns out to be right it will be big news.

Second, I would send cameras to take close-up pictures of the surface in many areas, using landers and roving vehicles, or better yet, a drone plane or balloon doing detailed low-altitude aerial photography. I'd send the pictures home and look for fractals or unexpected forms. This mission has the merit of being a worthwhile next step in the exploration of Venus, even though in all likelihood we will find no signs of life

Should we design and send a mission to test out any of these ideas? I don't know. They are certainly far fetched, almost certainly not true. On the other hand I don't think this is any more far fetched than possible life on Mars, and I don't think the Viking biology experiments were in any way a mistake. If we found life anywhere else it would tell us more about ourselves and how we fit into the universe than any other discovery I can imagine. The best thing to do is combine exobiology studies with more straightforward planetary exploration experiments, so we are sure to get something worthwhile back from our missions. This was the approach with Viking, which didn't find life but taught us a huge amount about Mars.

IS VENUS COMMONPLACE?

Now that I have gotten those flights of fantasy out of my system, it's time to come back down to Earth - or at least to Venus. There is another reason why the possibilities of life on Venus may not be completely academic to students of exobiology: there are probably more Venus-like than Earth-like planets in the universe. Admittedly, our available sample of terrestrial planets is so limited that any statement about what planets in general are like should be taken with a huge grain of salt. When you hear anyone make definitive statements about planets in the universe your b.s. detector should go immediately into the red. Nonetheless, we can observe that in our ensemble of terrestrial planets, to the extent that there is a "normal" atmosphere, it is mostly carbon dioxide, with traces of other things. Earth is the misfit, weirdo planet, and we are not sure why. We know that life is involved, but cause and effect here is muddled. Recently, we have decided that the best explanation for the existence of our strange, giant moon is that Earth got clobbered by a Mars-sized stray planetesimal very early in its history. This event may have had major effects on the physical characteristics of the Earth, and in particular may have drastically changed the atmosphere in ways that no one has figured out yet. Do we owe our weird atmospheric evolution, and subsequent friendly locale for "life as we know it," to this fluke? If so then Earth-like places might be very rare. Most Earth-sized planets might be more like Venus.

ARE WE ALL VENUSIANS?

It is just possible that our voyages to Venus are a journey back to our oldest ancestral home. If Venus, Earth and Mars all started out with oceans full of organic chemicals, this "soup" might have cooked up carbon-based life on any of them. If life formed anywhere on the early terrestrial planets (and it seems that it did...), it could have spread to all of them. In their early years, the planets may have been highly contagious. Their earliest environments were often disturbed by large impacts from the heavy bombardment that marked the final stage of planet growth. Such events can launch rocks off of one planet that eventually land on another. We know that this happens because we have already found about a dozen meteorites from Mars here on Earth[21]. Early life could have traveled from planet to planet, hitch-hiking across space on the impact debris that was blasting between them. In this scenario our carbon-based ancestors could have originated on Mars or Venus. - or Earth could have infected these other worlds.

Venus might have been the best place of all for organic life to get started. Our sun has been heating up steadily over the 4.5 billion years of its existence. Sunlight was dimmer by about 40 percent when the sun and the planets were very young. This means that, depending on the details of atmospheric evolution, all of the terrestrial planets might have been a lot colder. Earth and Mars may have been too cold, and Venus "just right" for life of the water-borne variety. If life did form on Venus and spread to the other planets it must have emigrated quite early, since our ancestors were certainly here 3.8 billion years ago. On Mars the poor little buggers would eventually have been freeze-dried by subsequent global change, whereas on Venus they would have been broiled, unless they found a way to live in the cool clouds and eat acid.

We may have gotten started on Venus. If so, then our spacecraft are the first calling cards of a prodigal sister, returning home after living for billions of years on another world.

LONG LIVE MAGELLAN

We know, for sure, that there are signs of life at a few places on Venus. We know because we left them there - the smashed, corroding remains of our inquisitive machines. The most recent addition to this smattering of Earth-junk is whatever is left of Magellan. If Magellan could have asked us, it might have requested to be cremated and have its ashes scattered around Venus. That's pretty much what happened to it[22]. There could be no more fitting end for the spacecraft that brought a world alive for us.

By early October 1994 it was clear that the end was at hand. We had completed most mission goals, and funds were running dry. The spacecraft was losing power rapidly, its solar panels finally giving out after seeing Magellan through more than 15,000 orbits. Magellan could have been left circling around Venus, but its low orbit would have decayed eventually, and it would have met the same fate. Instead, it was done in by an "assisted suicide" that allowed us to perform one final experiment. On October 11, 1994, five-and-a-half years after it was launched from Earth, we fired thrusters to lower Magellan's orbit into the upper atmosphere. The wing-like solar panels were rotated to make a windmill shape, and we

---

[21] One of these Martian meteorites, Nakhla, actually struck and killed a most unlucky dog when it fell in Egypt in 1911. There are probably Venusian meteorites too, but we haven't identified any yet.

[22] I really want to say, "them", that's what happened to "THEM!" This feels like talking about the death of a friend, not just a machine.

measured the increasing thickness of the upper atmosphere by watching how Magellan spun as it plunged. Magellan died as a kamikaze corkscrew for science, sending home new information until the end.[23]

Our tracking stations lost Magellan's signal for the last time at three in the morning, California time, on October 12. We can pretty much guess what happened after that, as Magellan finally entered the world it had circled and scrutinized for years. The solar panels and large main antenna must have been torn off first. Then various smaller pieces would have started to rip off, some igniting in the growing heat from friction with the increasingly dense atmosphere. But Magellan entered fairly slowly and probably did not burn up entirely. The larger chunks probably fell to the surface, where they would have landed gently because of the dense atmosphere, like shells settling to the bottom of the sea. Judging from Magellan's location at the time of its final transmission, some pieces may have landed on the high peaks of Maxwell Montes. Maybe some day the Smithsonian will offer a prize for the first Magellan-part found and returned to Earth.

We have not yet thoroughly analyzed, much less understood, the huge wealth of data dumped on us by Magellan. It takes a while to digest a world's worth of images, re-evaluate our home world in light of the data deluge, and develop a new understanding of Earth-like planets. The big picture of Venusian evolution is still shrouded in clouds, now patchy and thinning in places, which will continue to be slowly dispersed by mature reflection.

We've learned a lot about Venus and we will learn a lot more by carefully studying our Magellan images over the decades to come. But we still need a lot of answers that we will have to go back to Venus and ask for.

BACK TO VENUS

How soon and in what style will we go back to Venus? The answer largely depends on political and economic developments - things that are even more complex and hard to predict than planetary evolution. There is no shortage of plans and ideas for further exploration, some of which would not be too expensive. The more we learn about other planets, the cheaper it gets to learn more. We don't need another huge mission like Pioneer to learn an awful lot. Now we know better what questions to ask, and how to rephrase the questions more precisely so that Venus is less likely to give elliptical answers. Knowing what we know now we could send some small, low cost, focused missions which would be very fruitful.

We could put a small craft with a few carefully chosen instruments in orbit around Venus, or land a very small package on the surface, for a ballpark figure of 200 million dollars, less than a buck for each American.[24] More ambitious missions involving multiple landers or

---

[23] This has been called Magellan's atmospheric "re-entry", but that doesn't seem quite the right term for a spacecraft launched from another world.

[24] This is how much it cost to make the movie "Waterworld", and roughly the sum being sought to build another football stadium in Denver. (I told you it was a ballpark figure.)

experiments requiring long survival times at the surface would be considerably more expensive. We might pursue these as international collaborations, sharing around the Earth the cost of exploring Venus.

You may have noticed a pattern in my descriptions of our planetary missions. There is always a grandiose list of questions we hope to answer with the promised new observations. Later, when I describe what we have actually learned from the Mariners, Veneras, Vegas, Pioneers and Magellan there is a lot of ambiguity, and the results must be couched in caveats and uncertain assumptions. We hardly ever get complete answers to the original questions, but we always discover things we were never looking for.

This is just a reflection of the way our science works. To justify a mission (to ourselves, to Congress, to the public) we need a list of well-defined questions, but real planets are complex, messy and full of ambiguity. Many of the benefits of exploration simply can't be anticipated. If we knew exactly what we would find there, why go?

Having said that, here are some questions for future missions:

What is the unknown ultraviolet absorber?
What drives the superrotation of the upper atmosphere?
What is stabilizing the climate?
What is the chemical composition at the very bottom of the atmosphere?
Our evidence about the part of the atmosphere actually in contact with surface rocks is vague, contradictory and confusing.

What is the composition of the "noble gasses?"
Pioneer and the Veneras gave us only vague answers. Precise values could help us pin down the history of the atmosphere.

What is the effect of a "supercritical" lower atmosphere?
This is something I haven't discussed here, and no one has worried about it too much yet, because we have had so much else to think about. The atmosphere at the surface of Venus is neither a gas nor a liquid. At the high pressures found there, that distinction breaks down, and CO_2 is "supercritical." We are used to thinking of the atmosphere as a gas and that Venus has no liquid oceans. In fact, the lower atmosphere of Venus may truly be as much a liquid as it is a gas. This could have a major influence on the chemistry and radiation down there, and other aspects of the environment as well. How would this affect the climate-sensitive chemical feedbacks between "air" and rock at the surface?

How old are the various kinds of terrain?
For example, how old are the tesserae? Are they all the same age? How old are the plains? What are the ages of flows around young shield volcanoes?

What types of minerals and rocks are present?

Ideally we would want answers from many locations, sampling rocks from Tesserae, from the rolling plains, from a young shield volcano, from a pancake dome, and from Ishtar and Aphrodite, for starters.

What is the "snow" at high altitudes?
What is the present rate of volcanic eruptions?
What gasses are volcanoes exhaling now?
What is the interior structure?
It would really help to know the thickness of the lithosphere and how much it varies from place to place, and the overall density distribution and motions of the mantle. Does Venus, like Earth, have a solid inner and liquid outer metallic core?
What does the surface look like up close?
Magellan's radar uncovered the surface for us at a certain scale, but we still don't know what it would look like to us, up close, in visible light. The answer will be different at different places, and we won't know until we send cameras.

Here are several possible new missions that could answer some of these questions (and probably force us to ask a lot of new ones that we can't even imagine now):

Orbiter: Since the last time we had an orbiting spacecraft to study the atmosphere of Venus, we have discovered the "near infrared windows" that I wrote about in chapter three. An orbiting spacecraft with cameras tuned to these windows could do fantastic things. This instrument would be similar to the NIMS instrument on Galileo (described in Ch 3), but optimized for Venus. Even in Galileo's brief fly-by of Venus in 1990, NIMS provided us with an invaluable 3-dimensional snapshot of the clouds. Long-term monitoring with such an instrument would reveal changing structures and motions at all levels in the clouds and possibly provide clues to the nature of the superrotation. It would also allow us to peer through the infrared windows and observe changes in the lower atmosphere. Maybe we would find the "smoking volcano," - catch Venusian volcanoes in the act of erupting by sensing the infrared signatures of their gas plumes. Thus, even from orbit, we could learn about the composition of the volcanic gasses and the ongoing eruption rate. An orbiter could also carry an ultraviolet spectrometer for further study of the unknown absorber.

Airplanes and Balloons: The Soviet Vega mission of 1985 pioneered the use of balloon stations in the Venusian atmosphere. We could do a lot more along these lines. By setting balloons adrift in the atmosphere, we could learn about circulation patterns. On-board instruments could measure atmospheric composition and study cloud drops. At lower altitudes, cameras on balloons could photograph the surface as they circled the planet, getting a free ride from the supperrotation.

A slightly more elaborate approach to the balloon exploration of Venus is the aerobot. These are robotic balloons that could adjust their buoyancy to control their altitude.[25] They

[25] We can do this with a "reversible fluid" that changes back and forth from gas to liquid. When you cool it and it condenses to a liquid, the balloon is denser than the surrounding air and

could make brief forays down to the hot lower atmosphere and possibly even land on the surface to do experiments or drop off small instrument packages. When they started to get too hot, they could retreat to higher altitudes to cool off, ride the global winds around the planet, and radio home their findings from the latest venture to the depths.

Drone airplanes or blimps could fly low over the surface, photographing large areas.

Entry Probes. One probe, building on the heritage of the Pioneer designs but carrying a new generation of experiments, would answer many of our lingering questions about the atmosphere. Experiments pinning down the composition of the lowest part of the atmosphere and getting more accurate measurements of the noble gasses would help us understand the origin and history of the atmosphere and the current climate balance. Such a probe could also study cloud particles on the way down. Another idea is a "multiprobe mission" that would deliver a large number of very simple probes consisting of radio transmitters. By tracking their positions and motions as they fell, we could gain a comprehensive picture of the global atmospheric circulation.

Landers: We would love to land more instruments to study the chemistry of surface rocks, test the air, and take more pictures. Now, after Magellan, we know where to look. A sample each of tessera, young flows from a shield volcano, plains basalts, "river" beds, pancake domes and shiny highlands would clear some things up.

Sample Return: As sophisticated as some of our robot spacecraft experiments are, they don't hold a candle to what human scientists can do in a good lab on Earth. There is only so much that you can do remotely with a robot lander. To really study Venus rocks in detail, we would need to send a probe that could pick some up and bring them home to Earth. That is the only way to measure the age of a rock from its radioactive decay products. Ideally, we want samples from several different places in varied geological settings to get a handle on the age distribution. (This takes us well out of the $200 million range, by the way).

Here's a sick thought: Some recent research suggests that Venus is a common destination for fragments blasted off our Moon in large impacts, so Moon rocks are probably scattered around its surface. When we do finally get a mission to go to Venus and bring back a rock, we had better be careful not to grab one of these expatriate Moon rocks. That would really screw up our analysis!

Long duration surface stations: Studying Venus is like opening one of those Russian dolls with another doll inside and another inside that one. Each layer opens to reveal another layer of mystery. We've finally found our way through the clouds to see the surface, but to fully crack the puzzle of Venus we will need to look below the surface. A network of seismic stations could

---

descends. Heated, the fluid evaporates and becomes a gas, lowering the balloon's density and causing it to rise.

allow us to do that. If we could map the interior density structure of Venus as we have mapped Earth's, a lot of our uncertainty about how surface structures manifest the motions below would instantly be resolved. Seismometers would allow us to see how another Earth-like (and Earth-sized) world has organized its insides.

This would not be cheap or easy. Any experiment requiring long-term operation on the surface would require a whole new generation of electronics and materials that could survive and function at Venus temperatures. But we could do it if we set our minds (and our wallets) to it. We are now studying the idea of a mission that would place three seismic probes on the surface, with refrigeration to keep them cool long enough to gather some data and return it home. Of course, we don't know how seismically active Venus is, so any experiment like this without long expected survival times is risky.

Of all these ideas, the two that most excite me are cameras and seismometers. A seismic network any time soon may be prohibitively expensive, but we must send cameras to photograph the surface of Venus. There are surely places of fantastic beauty and complexity with intricate details and colors invisible to orbital radar. A low-altitude flying machine that covers a lot of ground would be the ideal platform.   First, just to guarantee that we find something interesting, I'd go to some of the young volcanic areas. If you look up close, young volcanic places like Hawaii show a riot of interesting and diverse detail.

On Venus you should see just as many interesting forms, but they would be different because other kinds of lavas are erupting into a very different environment. On Earth, undersea volcanoes produce bizarre pillars and pillows of lava unlike anything seen on land, and you could bet that the volcanoes of Venus would also be full of delightful surprises. Also, since erosion on Venus is so incredibly slow, many geological forms would be remarkably well preserved. This is a characteristic of some of the most beautiful places on Earth. We could fly over the high peaks of Venus and see whether they look shiny in reflected light, then head down an ancient winding river valley. We could cruise low over Devana Chasma and see how closely it resembles the East African Rift Valley. If we are lucky, we could catch a young volcano in the act of creating brand new parts of Venus. [photo of undersea volcanic pillars]

I have to admit, my desire for photographs of Venus is aesthetic as much as scientific. I want to know what it looks like! But why even make the distinction?   Such an endeavor could not help but be scientifically useful. To see is to gain understanding. The quest for vision and the quest for scientific knowledge blend seamlessly. Beauty and mystery are reason enough to explore.

How much money should we spend on future Venus missions or planetary exploration in general? It's not easy to say, at a time when we have so many urgent needs here. Our species is starving and we are trashing our planet. Our schools are falling apart, funding for the arts has all but dried up, and our inner cities are so troubled.   Tough times require tough choices. But we are learning how to explore more cheaply all the time. I believe that maintaining a robust program of robotic exploration is a good deal in the long run. Just to provide some perspective, one B-2 "stealth" bomber costs about a billion dollars. For less than the cost of a fleet of these we could fly all the missions listed above.   The benefits are as intangible as they are ultimately vital to maintaining and enhancing the planetary perspective that may save us from ourselves.

A LONG HOT VENUSIAN AFTERNOON

If people ever do go to Venus, what kind of a place will they find? What's it really like there? Well, as on Earth, it depends on where you go. But there are some qualities of the environment that would immediately strike anyone who landed there and stepped out of her ship. Let's assume you are well insulated against the heat and pressure, so you will live long enough to perceive other things. The first thing you would probably notice would be the quality of the light.

We think of Venus as a bright, luminous planet, but if we went and spent some time on the surface, the light would seem dim and diffuse. It's relatively dark there for the same reason that the planet glows so brightly in the skies of Earth: most of the light is reflected back into space by the clouds. But there is plenty of light at the surface to see (like a deeply overcast day on Earth) and your eyes would quickly adjust. The most striking characteristic of the light would be its deep red cast, a permanent sunset color that results from scattering of light by layers of thick atmosphere and clouds. Looking up into that deep red sky, you might learn to judge the time of day by the slow movement of brightness across it, but you would never see the sun, and there would be no shadows (terrestrial vampires would feel at home).

I've said earlier that the sky is an unbroken, unchanging overcast. I was repeating what I've heard many times, which always seemed reasonable enough. But now I'm not so sure. Now we know how patchy the clouds are. As I described in chapter 3, recent discoveries in the near-infrared "windows" showed us that the bottom layer of clouds, where most of the cloud mass is and most of the light is blocked, is full of holes. Although we never saw them with earth-based telescopes or orbiting spacecraft not tuned to the right infrared channel, we now know that there are thin and thick patches of all shapes and sizes down there. On the night side, in the infrared, the places where the clouds are thin appear as "hot spots" from which the heat radiation shines out to space. (as seen in the Galileo picture on page N). On the day side, I suspect we would see these as brighter patches in the sky. On overcast days here on Earth we still see bright and dark patches of sky where the thickness of the clouds varies. I think we would see the same thing on Venus. The contrast between the "hot spots" and "cold spots" on the night side is huge - some places are 10 times as bright as others. Some of the spots are hundreds of miles across. I think the biggest and brightest patches could be seen from the ground. If so, the sky of Venus becomes a lot more interesting because it would be constantly changing.

Furthermore, the superrotation of the upper atmosphere would be rendered visible from the ground. These cloud patches would move a thousand miles from eastern to western horizon in about 5 hours. What a sight that might be: giant shifting shapes of light and darkness slowly forming and dissolving as they traversed the sky 30 miles overhead. You might sense subtle changes in the light around you as large thick and thin patches of cloud passed by above. Standing on the ground, the air around you would be very still, perhaps broken occasionally by a very light gust of searing wind. But glancing upwards you would see a constant reminder of the raging winds that circle the planet.

That's the daytime. At night, things could be considerably stranger. At midnight the sky is completely dark, and the main source of illumination is the glowing of the red-hot ground!

The surface is so hot (almost 900o) that its thermal radiation would produce a faint red glow. The darkness might also occasionally be broken by a faint flash of lightning from high above in the clouds[26].

It's not just the quality of the light but the pace of its changes that would tell you immediately that you are not in Kansas any more. On Earth, day and night last roughly 12 hours, depending on the season and your latitude. The terminator (the line between day and night[27]) sweeps across the landscape at 1000 miles per hour at the equator, and is slower at higher latitudes.[28]

On Venus, day and night each last 59 Earth days, or about two Earth months. The terminator is a diffuse boundary that strolls from West to East at a leisurely 8 miles per hour at the equator. At a high latitude, say Maxwell Montes at 70oN, it would move at 3 miles per hour. So if you stayed in one place you would have to wait a very long time for the light to change, but it might be worth the wait. As twilight approached, the sky would very slowly dim and the glow of the ground would become noticeable. Maybe it would feel like those enchanted times on Earth when the landscape is illuminated by a slowly shifting balance of full moonlight and fading twilight. Dawn would bring a similar slow changing of the guard from ground-glow to sky-glow.

This leisurely pace of change could have its advantages. On Earth, if you are traveling in a jet aircraft, you can play tricks with the time of day. Traveling westward at the right speed, you can make sunset last for a very long time. Traveling eastward, the night passes quickly. On Venus the changing of the light is so slow that you could do these things on foot! Remember how St. Exupery's Little Prince kept moving his chair around his asteroid to watch the sunset over and over again? Similarly, if you had a favorite time of day on Venus, where the light was perfectly balanced between ground and sky, you wouldn't have to wait for night to fall. You could just walk there.

Some of the most interesting places to be on Venus, in terms of the quality of the changing light, might be near the north and south poles. Here you might find a perpetual twilight, a balance between the constant ground-glow and the sky-glow that SLOWLY travels around the horizon, as Venus spins.

Because its spin-axis is not tilted like Earth's, Venus has no seasons, but the changing time of day there has the pace of seasonal change here. A month-long afternoon is followed by several weeks of twilight before night fully falls. All of this refers to changes in illumination, not temperature. If you become overheated during a long, Venusian afternoon, and you want to cool off, don't bother to wait for dark. Not only is it a long wait, but the temperature doesn't change. Going north or south to the poles won't help either. The thick atmosphere of Venus redistributes heat so that time of day and latitude have no effect on surface temperature. If

[26] We are still not sure whether there is lightning on Venus. We've recorded some suggestive electrical pulses, but we have yet to observe the telltale flash.

[27] Not a beefy robot sent from the future

[28] You multiply this by the cosine of your latitude, so that at 45° it moves at about 700 mph. It also changes with the seasons.

you want instant heat relief, climb a mountain.[29] Everywhere on Venus, it gets about 5 degrees cooler for every thousand feet of altitude. The high peaks of Maxwell, towering 38,000 feet above the plains, are a cool 710 degrees in the shade.

Walking on Venus might be easier than on any other planet, if we could design a survival suit that was not too cumbersome. Remember the images of Apollo astronauts stumbling and bumbling around the lunar landscape, occasionally falling and taking expensive pieces of equipment with them? They had to devise a whole new way of walking, or hopping, to get around in the Moon's low gravity, which is 1/6 Earth's. Our way of getting around on our planet is deeply tied to its gravity. But your weight on Venus would be only 10 per cent less than here, so you would not need a new way of walking. In fact, this would give you an added lift, an extra spring in your step, without really throwing you off.

As for what its like at different locations, there are probably as many answers as there are places. Personally, I would love to stand on the banks of one of the rock-rivers and see if it really looks like a river on Earth, or hike up the side of a shield volcano, searching for a bubbling lava lake. We won't really know what it's like there until we go and find out.

OH WE, LIKE CATS

"One of these days these boots are gonna walk all over you."

-- Nancy Sinatra

But will we go? We've sent our machines there, and will continue to do so. But will humans ever walk on Venus? Human exploration of space has slowed to a crawl. This seems to be part of a larger collective lack of nerve, a wave of self-doubt and fear of the future that we are experiencing as we approach the millennium. We are wondering what we have done to ourselves, other species, and our world. We are struggling with our addiction to high technology: we need it, we love it, and yet we have not completely learned how to live with it in a non self-destructive way.

Maybe we need to slow down, catch our breath, and get our own house in order before heading out into space again. After all, look what happened the last time. We went to the moon without really knowing what we were doing or why we were doing it, and it didn't stick. We then retreated so thoroughly that we can't even get back there today. Apollo was quite an achievement, but when we send people to Mars or even eventually to Venus, it would be better to have a clear, long-term plan.

I have a fantasy of cloud-cities on Venus, huge enclosed habitats suspended from giant balloons. At a certain altitude where the temperature and pressure would be comfortable for us, we would mostly just have to keep the air fresh, maybe by collecting solar energy to make oxygen from CO_2, or better yet, growing plants to do the job for us. Why should we bother to do such a thing? I don't know. These could be research stations, or maybe there will be some

---

[29] Summer time in Tucson, where I lived for 7 years during grad school, is pretty much like Venus, always hot in the desert, day and night, always cool up in the mountains.

economic incentive, something rare or beautiful found only on Venus. Or maybe, in the very long run after we have solved all our major problems here on Earth, we will go just for the hell of it, because it is there. (Yes, now I really am fantasizing.)

Anyway, it doesn't really matter what I say here, or anyone else writes in any book. Generations from now, I think, we will explore the clouds and the surface of Venus in person. I can't think of a rational reason to go, but we humans will always keep exploring, perhaps because it is our destiny, or because we can't resist knowing what lies beyond that closed door. If you have ever lived with cats, you know that they will get into anything new or mysterious that appears in the house. Any unexplored frontier compels them. They will keep trying until they get inside. Humans are a lot like cats, so curious that we must poke our heads everywhere, look around every corner, under every curtain and behind every door, even when it might get us into trouble. We will continue to explore the universe for the same reason cats explore closets. Like cats, we also sometimes have more impulsive curiosity than foresight. It's easy and fun to climb up the tree, but now how you gonna get back down? (Where you gonna bury that nuclear waste?) But we are capable of learning. You know what curiosity did to the cat, but we are a bit smarter.[30] I know that's not saying much, but if our curiosity is augmented with wisdom, if we integrate what we find along the way into a new, larger and longer perspective, I think we will go far.

TERRAFORMING AND VENERAFORMING

"Earth First! We'll mine the other planets later."

-- bumper sticker seen outside Telluride, Colorado

"The mutation from terrestrial to interstellar life must be made, because the womb planet itself is going to blow up within a few billion years...Planet Earth is a stepping stone on our time-trip through the galaxy. Life has to get its seed-self off the planet to survive."

--Timothy Leary

Venus today may not seem like a place where anyone in her or his right mind would ever want to go. Could we re-make it in Earth's image? This idea is as tantalizing in some ways as it is horrifying in others.

Various schemes have been dreamed-up about how we might one day alter the environments of other planets to be more like Earth, so that we could go live on them without needing suits or domes. This is called "terraforming." Most schemes focus on Mars because it already has the most Earth-like surface conditions and so would need the least work.[31] These

---

[30] if physically somewhat less resilient, and each possessed of 8 fewer lives...

[31] This may seem far out to you, but hey, Las Vegas and Tucson have been terraformed, at least temporarily, so anything is possible.

plans are somewhat cartoon-like: "All we have to do is add 20 zillion tons of oxygen and then plant some geraniums." They tend to focus on what is needed for life and ignore hazards that may be present. For instance, if we created a warm, oxygen atmosphere on Mars, what poisonous trace gasses might also be there, oozing out of the rocks? All of the schemes are fantastically expensive and impossible given our current technology. The impossibility of doing these things, for now, absolves us from the responsibility of deciding whether we should.

On Venus, the major impediments to our comfort are the temperature, the pressure, the unbreathable CO_2 atmosphere, and the lack of water (otherwise it's quite nice!). Terraforming schemes all focus on getting rid of large amounts of CO_2 and converting some of it to oxygen. This would solve three out of four problems. Then, just add water and voila! There is another problem that some of the schemers and dreamers do not consider: if Venus had Earth's atmosphere but retained its very slow rotation, daytime heat and nighttime cold might be unbearable. It's hard to say what kind of weather would result. So, while we are scheming, we should also figure out how to spin Venus up to a more "normal" rotation rate.

In brief, here are four ideas proposed to "fix" Venus to be more like Earth:

1) Pummel it with asteroids and comets, blowing off a lot of the atmosphere and adding cometary water. A coordinated targeting could also help speed up the spin.

2) Make large dust clouds in the upper atmosphere that would shut down the greenhouse effect and cool the planet. The asteroid pummeling mentioned above would help here by kicking up quite a dust cloud on its own.

3) Use orbiting sunshades to cool off the planet enough to condense out the CO_2. Then cover up the resulting lakes with reflecting fabric, so they don't evaporate back into the air.

4) Seed the clouds with algae that convert CO_2 to O_2. Genetic engineering could provide custom bugs that enjoy life on Venus and eventually make it more like Earth.

These schemes may all seem a bit fantastic, silly even. Each of them has been discussed in much more elaborate terms, with detailed calculations of the energies and timescales involved. This doesn't make any of them sound a lot more credible though. The least offensive and the most doable is the last one. Biological solutions do not take huge amounts of energy because they use the natural, exponentially multiplying quality of life. If we found or created a suitable organism, we would only need to introduce a small amount and it would eventually spread and transform the planet.

One more possibility is worth mentioning. In chapter 5 I pointed out that some new evolutionary climate models hint at instability in the climate of Venus, or at least the potential for instability that we might be able to trigger. If so, we might use a minor application of any of the above schemes to jump-start a runaway cooling. Cool things down just a little , and surface-atmosphere chemical reactions might remove CO_2 from the atmosphere, reducing the greenhouse effect and cooling things still further. The resulting feedback loop would cause the climate to decay to a condition we would find more comfortable.

These schemes seem impossible and perhaps unethical, so why even bother to discuss them? Well, today's impossibility is tomorrow's engineering project. Who would have thought, 100 years ago, that we would have walked on the moon (and then abandoned it!) by now? The dreamers are sometimes the advance wave of the next revolution. But there is a much better reason to be talking about this now. Thinking about terraforming is good intellectual sport. It's fun, and it stretches our mind-muscles in useful ways. Fantasizing about how we would terraform other planets helps us think about how planets and climates work and how they might change. Thinking about changing planets in a purposeful way is especially good for us, because we have been changing our own planet in random, haphazard ways. We need to learn how to take a more collective, constructive approach to altering our planet's environment. By imagining how we could do this elsewhere, we enlarge our understanding of global change. Any successful terraforming project would take generations to complete. It's good for us to practice thinking about global change on such long timescales. In fact, our survival will depend on our learning how to do this. The value of thinking about terraforming is that it can help us learn how to stop veneraforming our own planet! (making it more like Venus.[32])

Understandably, talk of monkeying around with planets makes many people uncomfortable. There is a natural resistance to such ideas, given our sorry recent history of tinkering with this world beyond our ability to foresee, or cope with, the consequences. There is a strong reaction against the human arrogance of thinking we can "play god" with the solar system when we seem to be barely able to manage our affairs down here. We do have a history of charging off and "exploring" places in an intrusive and impulsive way, messing things up, then realizing it later and issuing half-hearted apologies. We must learn from this, and step mindfully into the Solar System. At the very least, we should hold ourselves to the standard of being able to consciously terraform Earth (rather than unconsciously veneraforming it as we are doing now) before we take on other worlds.

Finally, there is a further moral dimension: Do we know for sure there is not extant life on Venus or Mars that we would be destroying? We must be much more certain about this than we are now before we risk, in our ignorance, wiping out a biosphere.

Even so, we may one day decide that it is a good idea to transform other worlds. If we ever determine, for sure, that, say, Mars is utterly lifeless (something not possible with our current scientific abilities) then the ethical imperative changes. Propagating life is arguably a good thing, and preserving life is certainly a good thing. If we want to insure that Earth life, including humans and other creatures, survives the planetary disaster that surely will come some day (by asteroid, comet, human stupidity or something unanticipated), we must gain permanent outposts beyond Earth. Mars and Venus may eventually be options for this kind of trans-planetary life insurance policy.

We are community, within and without.[33] It's only natural to want to extend this and create an interplanetary community. There is beauty and inspiration in the vision of

---

[32] See "Venus Envy" in chapter four.

[33] That is, our bodies are, in a sense, communities of microorganisms, and our biosphere is an intricate mesh of interacting communities.

humanity's spreading into the galaxy, leaving the cradle, becoming who-knows-what. Throughout my teenage years, this was one of the guiding visions of my life. I have since gained a healthy respect for our current limitations. I still believe in the vision, but I think we have some major tests to pass first. We have to do our homework before we can graduate to being a wise, space-faring species. To survive, thrive and possibly expand, we must learn some of the lessons Earth is trying to teach us right now - lessons about our limits and our interconnectedness, lessons about what it means to function and live sustainably as part of a planetary community.

Fortunately, it will be a long time before we are capable of terraforming, so we can mull over the ethical implications for at least a century and perhaps several. Maybe we will decide that it is not such a good idea. Terraforming will remain a purely intellectual exercise for the foreseeable future and, as such it is fun, and arguably worthwhile to fantasize about. But if anyone suggests seriously that we embark on any of these schemes any time soon, they should be institutionalized, or forced to teach Freshman Astronomy at a large public university. Any actual plan to implement such changes would be the height of folly until we learn a lot more about life, about planets, and about ourselves.

OUR PLANET OURSELVES

"Destiny is not a matter of chance, it is a matter of choice;
It is not a thing to be waiting for, it is a thing to be achieved."
--William Jennings Bryan

"Space ain't man's final frontier. Man's final frontier is the human soul."
-- Arrested Development

"Human history becomes more and more a race between education and catastrophe."
-- H.G. Wells

"Remember, the mountains don't care."
-- sign at trailhead, Rocky Mountain National Park

In earlier times Venus was an object with great spiritual significance. Hundreds of years ago people in Mesoamerica and many other places saw it as an animated presence closely connected to the underworld and to human origins. In the last 400 years we have seen Venus take on many personas, heavenly and hellish. The ideas and models we have used to describe her reflect changes in our views of ourselves, our relationship with our world and - once we knew there was one - with the larger universe. Now we find that in some important ways Venus is a long lost sister to the Earth, a nearby world that is complex and active like our own. This is no demotion in status: being a twin to our home planet is not a lesser thing than being a god.

The human race and the planet Earth are at a crossroads now. Our recent spurt of new knowledge about Venus comes at a time when we are once again re-evaluating our relationship with our planet. From one perspective, the Earth was doing fine before we came along and will be better off if we do ourselves in. But this view overlooks the unique and precious attributes that we, with all our failings, bring to the planet. After all we are, as the song goes, the eyes of the world, as well as the brain, heart, mind and soul. Surely the world would hum along without us and perhaps be grateful for the end of the ruckus, but it may be left in a brain-dead state, especially if we take the dolphins and chimps out with us. I don't mean to suggest the conceited notion that we are the only intelligent species that will ever inhabit this corner of the universe. Given a little time someone else will find it useful to become self-aware. Perhaps elephant herds or termite mounds given a few million years will surprise themselves by learning to use tools and language. I would even question whether the term "intelligent" applies to us. I would suggest the following test: a species may be considered intelligent if it is capable of taking care of itself and other species, of foresight and collective action, and especially of not overpopulating and soiling its own pen to the point of extinction. By this definition it is not at all clear that intelligence has yet evolved on Earth. Perhaps that explains why no one has answered our first radio messages to the cosmos, our interstellar Chuck Berry records, or even the re-runs of My Favorite Martian that have now spread tens of light years into the galaxy. Human-bashing is one popular response to our current dilemmas. But right now we are the only game in town, so what can we do but try to survive and act "intelligently"?

We face the self-imposed challenges of overpopulation, resource depletion, global warming, ozone destruction, and the slow spread of chemical poisons known and unknown. There is a growing realization that we need to change the way we operate within our planetary home. Various individuals and groups have their schemes, but there is widespread disagreement, disillusionment, cynicism and skepticism. It's a frightening situation: we know we need to change the way we do business in order to survive, but we don't know how!

As a species, we are going through a painful adolescence. We are self-aware but not yet in control. We have many newfound powers but haven't given enough thought to what we should be doing with them. Somewhat aware of the consequences of our actions, we are not yet willing and able to take responsibility for ourselves. We are hooked on immediate gratification and not used to cleaning up our messes. We have little awareness of limits, and we love to watch things blow up. While we enjoyed the naive, infinite resiliency of youth, we could afford to be oblivious, but we are pushing the limits of our planet's capacity.

But adolescence is not all bad. A tremendous creativity and boundless exuberance makes the teenage years a lot of fun and teens so great to be around. We must harness that energy for survival, rather than suppress it. But how does maturity come? Partially through mentoring. It would be nice if some aliens who had already passed through this difficult phase would come and help us get a grip.[34] Unfortunately, we cannot count on this. We had better do it ourselves.

Maturity is also aided by an expanded reference frame, including knowledge of other places and new perspective on oneself. Perhaps the heightened planetary self-awareness provided by human encounters with other worlds can help us rise to this challenge.

---

[34] This is one of the themes of A.C. Clarke's "Childhood's End".

We have heard many variations on the saying, "They can put a man on the moon, but they can't [insert phrase here]". (My favorite is the funny/feminist ending "why can't they put them all there?".) It's true: we put several men on the moon, but we can't put food on everyone's table, stop fighting and learn to clean up after ourselves. Clearly science alone will not solve our problems. Some new technological tricks may help, but what we really need is the mass acceptance of new ways of thinking about ourselves. We need a widely credible and hopeful vision of our future.

The main obstacles to our survival at this point are not technical and scientific, but socio-political and spiritual. But in reaching out across interplanetary space to explore our sibling worlds, we need not separate scientific and spiritual quests. The Earth is our body, our home, and thus physical knowledge of planetary history IS spiritual knowledge of self.

Is it really in our nature to destroy ourselves, to ruin the Earth for our kind of life? Or are we just stuck for the moment, lacking a vision of how to proceed safely into the future? We have taken on and created for ourselves some large and very new challenges. Our biggest need may just be to look at our situation differently.

All this "collective" language is nice, but in what sense do we act as a species? We make decisions as individuals, groups, governments and corporations. How can we hope to solve problems that require a change in the behavior of humanity as a whole when we have no mechanisms to act collectively? The planetary perspective on who and where we are can help us here. A wonderful example is the depletion of Earth's ozone layer. We recognized this mistake through comparative planetology, and we seem to be on a course toward correcting it through planet-wide agreements. Planetary consciousness breeds planetary responsibility.

When we step back and reflect on what we have learned, the most important benefit of planetary exploration will be self-knowledge. Venus IS our twin, not identical, but recognizable, and full of the promise of enlarged perspective for Earth and its newly conscious residents. We should treasure every bit of knowledge and insight Venus can provide. It's the only twin we've got.

VENUS REVEALED David Harry Grinspoon

Part 6: 6/26/96