THE ENDLESS VOYAGE

"Building Blocks" Episode 118

One can come at the origin of life problem from all different sides. I suppose my way of coming at the problem is as someone who works at the interface between chemistry and biology and by definition, the origin of life is the birth of that interface.

You see evidence of life everywhere. And when we talk about the most primitive, minimal form of life, we're talking about a type of life that is not within our experience today.

One of the truly fascinating things about life is that it's remarkably, just absolutely, fantastically adaptable and resilient. It turns out that…there is no place that I know of—or almost no place that I know of on this planet that you can go, and there won't be something living there.

NARRATOR:
LIFE ON EARTH—RICH, VARIED AND ABUNDANT, BUT AT ONE TIME EARLY IN THE HISTORY OF THIS PLANET, THERE WAS NO LIFE, ONLY THE CHEMICAL CONSTITUENTS THAT WOULD AT SOME POINT COALESCE, AS THE PROCESS LEADING TO LIFE WAS SOMEHOW, SOMEWHERE SET IN MOTION.

J. WILLIAM SCHOPF, Ph.D., UCLA:
Life is made out of only a few elements. The principle ones are CHON, c-h-o-n, carbon, hydrogen, oxygen, nitrogen—and sulfur and phosphorus. They come in, too. So, "CHONSP," one can talk about, all right? Now those are elements that link together into making organic molecules. And the organic molecules are the things that life is made out of.

NARRATOR:
THERE ARE A NUMBER OF THEORIES THAT ATTEMPT TO EXPLAIN THE ORIGIN OF LIFE ON EARTH. THE ONE WITH PERHAPS THE MOST SCIENTIFIC SUPPORT IS SOMETIMES CALLED THE PRE-BIOTIC SOUP THEORY.

JEFF BADA, Ph.D., Scripps Institution of Oceanography, UCSD:
This was first formulated in the early part of the 20^{th} century, and what this says is that organic compounds that we associate with biology as we know it can be formed by natural chemical processes on the earth or elsewhere. And these compounds can then be dissolved in the oceans of the early earth. And in the oceans, they get transported all over the place, they end up interacting with each other, forming more and more complex molecules. And eventually you start producing some sort of complex, polymeric-type compounds that start to have this ability to replicate.

So when one talks about an organic synthesis, or a Miller-Urey synthesis, which is a particular type of making of organic molecules in the absence of life, what one is doing is knitting together these particular atoms into molecules. Now how do you do that? Well, it's done by energy. And on the early earth it was done by ultraviolet light, which tears apart molecules, but also can build them up. And by electric discharge—lightning in the earth's early atmosphere—that's another source of energy. And volcanic heating is another source of energy. Anything that has energy will do that.

BADA:
Stanley Miller showed in 1953, if you take a mixture of gases like methane, ammonia, hydrogen and you spark it, you end up making amino acids. This is a startling result. You take simple gases, put a spark through it like lightning, and out comes amino acids, which are the building blocks of proteins for all life on earth. Subsequently, other people have shown that if you take other simple gases, hydrogen cyanide being one, for example, that you can make the components of DNA and RNA. So this chemistry seems to be very robust, and you can make simple compounds. How they actually join up to form more complex molecules is still a challenging piece of chemistry. But we're making great progress here.

NARRATOR:
EQUALLY CHALLENGING IS TRYING TO DETERMINE WHETHER THE ORIGIN OF LIFE WAS A SPECIFIC EVENT, SOMETHING AKIN TO A LIGHT BULB TURNING ON.

GERALD JOYCE, Ph.D., M.D., The Scripps Research Institute:
Or was it a continuum of events, of chemical processes that somehow gradually moved over the threshold from what would be considered non-living to what is considered living. And I think it's a matter of your point of view and what working definition of life you subscribe to.

BADA:
A minimal definition of life is that the system has to be able to replicate itself. In other words, there's some way of taking the information that is stored in this entity, and duplicating it so it could be passed on to another generation. The other important aspect of this definition is that this replication has to be imperfect. You can't make exact copies. If you did, there'd be no change from one generation to the next and this system would just remain stagnant. But if you have random built-in mutations, sometimes you have copies that are made that, for some reason may have some sort of slight advantage over the precessor entities. And thus you have the evolution into more complex life forms.

I would put it this way, and this is not my phrase, this is the working definition that NASA, the civilian space agency, has adopted in their search for life and understanding of life. And so the so-called NASA working definition is as follows: "Life is a self-sustained chemical system that is capable of undergoing Darwinian evolution."

NARRATOR:
CHARLES DARWIN'S THEORY OF EVOLUTION BY NATURAL SELECTION IS BASED ON THREE FUNDAMENTAL PROCESSES.

JOYCE:
The first is amplification or reproduction. So parents make progeny, but if we think in terms of the origin of life, we're not thinking about organisms with feet that go running around. We might be thinking more about molecules that are able to become amplified to produce progeny molecules. So amplification is part one of Darwinian evolution. The second part is mutation or variation, because if all of the progeny were identical to the parents, there'd be no differences in a population. There'd be no grist for selection and evolution. So "mutations happen," to quote a bumper sticker, and so that results in variation among a population of individuals. So amplification, mutation, and then the third part of Darwinian evolution is selection. Selection is the process that operates on the population of variance to choose those that are most fit. So the subset of the population that is best able to withstand the environmental conditions or the vagaries of changing environmental conditions.

NARRATOR:
WHILE THERE IS GENERAL AGREEMENT WITHIN THE SCIENTIFIC COMMUNITY ABOUT WHAT CONSTITUTES LIFE, MAJOR QUESTIONS REMAIN CONCERNING ITS ORIGINS.

SCHOPF:
When did it begin? It dates from earlier than three and a half billion years ago, maybe as early as four billion years. So we have some notion about that based on scientific data. And the experts in the field think that the origin of life probably got started in a period of 10,000 years or maybe even 100,000 years at the maximum. And geologically, that's a very short period of time. And then the question is, "Where did it begin and how did it begin?" Well, we—I believe that there is widespread agreement on the three or four stages that led to life. You first have to make very small molecules—stage one. Stage two, you hook them up into longer molecules called polymers. Three, you get information like DNA—the stuff that's in chromosomes, the genes of humans and all other organisms. That comes along and that's one of these polymer-type molecules. That's the third step. And the fourth step is to encapsulate it into a cell.

NARRATOR:
WHILE THE PROBABLE SEQUENCE OF EVENTS THAT LED TO LIFE MAY BE UNDERSTOOD, THE PRECISE MECHANISM THAT TRIGGERED THAT SEQUENCE OF EVENTS REMAINS VERY MUCH A MYSTERY.

JOYCE:
If we don't know how life began, let's start from what we know. All life that's known on earth is of the same life form. One based on DNA as the genetic molecule that contains the information for the organism, and proteins that are the catalytic molecules that bring about the metabolic reactions. And so this DNA and protein-based life is the only

example we have. And yet you look at that life form and it's too complicated—it's too complicated to have imagined that DNA and protein-based life popped out of the primordial soup. So that leaves us with a gap between this more complex life and the chemistry that only existed on the primitive earth. Now a very important concept has taken a hold in the last decade or so in thinking about the early history and origins of life, and that is the notion of the so-called "RNA world."

And this is really interesting construct, where there was a period early in the history of life on earth where life consisted nothing more than self-replicating RNA molecules. Now today, RNA is the messenger that takes information encoded by DNA and translates that information into the structure—the amino acid sequence in proteins. So today, RNA has got this kind of peripheral role in life being a messenger. But early in the history of life, RNA may have been the molecule that did it all. It self-replicated, it catalyzed its own self-replication, and life consisted nothing more than simple self-replicating RNA molecules.

And so when people think about the RNA world, they say often that the RNA world solves the chicken and egg problem. Now what is the chicken and egg problem? Well, you have an egg—that's the gene—and it's going to describe how to hatch and create a chicken. But of course, you have the chicken—that's the proteins—that keep laying the new eggs. And that's how biology works. There's DNA eggs that encode protein chickens, which can lay more DNA eggs and the game goes on and on. But how do you start this chicken and egg business in the first place? Well, one way is you have a molecule, RNA, for example, that is both the chicken and the egg. It can act as the egg by encoding information, but like a protein enzyme, fold into a shape to catalyze chemical reactions, and carry out the laying of new eggs to also act as the chicken. So this is the paradox of the chicken and egg that can be solved if you have the right kind of molecule.

JEFF BADA, Ph.D., Scripps Institution of Oceanography, UCSD:
Eventually, again, through mutations and evolution, RNA—the RNA world evolved into the protein DNA world that characterizes modern biochemistry. And so you had sort of this sequence of primitive entities giving rise to RNA-based life, that eventually gave rise to DNA protein-based life. And once you got DNA protein-based life, you had a very efficient system for replication, catalysis, metabolism. Probably at this point the whole biological apparatus was compartmentalized in some sort of membrane and the whole process of evolution started leading to more and more complex entities.

NARRATOR:
INITIALLY, THIS PROCESS ALMOST CERTAINLY TOOK PLACE IN THE OCEAN. IN PART BECAUSE CONTINENTAL AREAS WERE VERY LIMITED IN SIZE. BUT PERHAPS EVEN MORE IMPORTANT, THEY DID NOT OFFER THE KIND OF CONDITIONS THAT WOULD HAVE BEEN CONDUCIVE TO LIFE.

TOM GARRISON, Ph.D., Orange Coast College:
The land was certainly an ugly place back then. It's somewhat moderated now because we have oxygen in the atmosphere and ozone layer to prevent UV from just cooking the surface. But back then, no, that was not an option. So the ocean is pretty much the place where those early chemicals got together to form self-replicative molecules.

NARRATOR:
SOMETIME AFTER THAT, IT IS BELIEVED THAT PRIMITIVE EARLY LIFE FORMS BEGAN TO APPEAR, LIFE FORMS THAT, AT LEAST ACCORDING TO DARWIN'S THEORIES, WOULD EVENTUALLY EVOLVE INTO MORE COMPLEX ORGANISMS. THE QUESTION, OF COURSE, IS WHY? WHAT EXACTLY FUELS THE PROCESS OF EVOLUTION?

JAMES NYBAKKEN, Ph.D., Moss Landing Marine Laboratories, CSU:
Why would this come about? Why wouldn't you just stay with jellyfish, for example? In order to exploit certain environments—that is, in order to move into certain environments, it was probably necessary to evolve organisms that had certain systems. Otherwise it couldn't do it. And the best example I could think of, is if you want to inhabit mud bottoms and burrow through mud bottoms, you have to have some way—you have to have a muscle system in order to do it, and it's probably a good idea to have a muscle system which is coordinated. Therefore you need a nervous system to coordinate that muscle system, otherwise you can't burrow. I can't imagine the jellyfish burrowing, for example, into a substrate. So here's a whole area of the seafloor that was only exploitable when muscle systems, nervous systems and so on came into being.

NARRATOR:
THE ABILITY TO ADAPT TO CHANGING OR DIFFICULT CONDITIONS, ONE OF THE FUNDAMENTAL PRINCIPLES OF EVOLUTION, IS CLEARLY NECESSARY IF AN ORGANISM IS TO BE BIOLOGICALLY SUCCESSFUL.

SEAN CHAMBERLIN, Ph.D., Fullerton College:
My interpretation of biological success would be that, really an organism fulfills his or her requirements to continue that line…essentially, that the species survives and reproduces. In another sense, biological success might mean that an organism moves into a particular environment that's perfect for its particular living conditions, has all the things it needs to live and survive and reproduce. It finds food and shelter, and so it proliferates within that particular environment.

NARRATOR:
DESCENDANTS OF SOME OF THE EARLIEST FORMS OF OCEANIC LIFE HAVE, IN FACT, SURVIVED, AND CAN BE FOUND IN THE MODERN OCEAN.

We have some very good fossil records going back to the Cambrian about 530 million years ago or so, some very fine fossil forms. If you look at those fossil forms, you will find that the descendants are represented in the fauna today. For example, I mean, we have lots of mollusks in the marine environment—snails, clams and so on. We have lots of arthropods in the forms of crustaceans—crabs and shrimp and so on. Those all came in the Cambrian, four or five hundred million years ago, so their descendants are here. Not the same ones, necessarily, but we do have the descendants.

NARRATOR:
FOR THOSE ANIMALS THAT ARE UNABLE TO ADAPT TO CHALLENGING CONDITIONS, THE OUTCOME IS GENERALLY UNFAVORABLE. THERE ARE A NUMBER OF REASONS THAT SPECIES SOMETIMES DO NOT SURVIVE.

One is that it was some other group of organisms which was better adapted for that particular environment comes in and out-competes them so that they disappear. And the other possibility is some event happened—let's say some change in climate or something happened—which changed the environment in which they lived, which they could no longer exist in that environment and that's a possibility, too.

NARRATOR:
THE ULTIMATE EXAMPLE OF AN ENVIRONMENTAL CHANGE LEADING TO THE TERMINATION OF A SPECIES IS WHAT'S KNOWN AS A MASS EXTINCTION.

DONN GORSLINE, Ph.D., University of Southern California:
We now realize that those changes are the result of perhaps catastrophic events on earth. Perhaps the one that's best known now is the boundary between the Cretaceous and the Tertiary, which is a time period something on the order of, oh, 80 million years ago, something of that nature. And at that time, the dinosaurs essentially were erased from the earth. And of course, that was a question that bothered paleo-biologists, paleontologists, for many years.

DONAL MANAHAN, Ph.D., University of Southern California:
Were dinosaurs maladapted—poorly adapted to the environment? Well, clearly not, they lasted for millions and millions of years, but then we know some major catastrophic event occurred in the climate and it made the whole group go extinct.

We now think that that was a result of a collision of a very large meteorite with the earth. And the result of that collision effectively removed many families—not just species, but many families of organisms from the earth.

But I'd like to add the following comment—I think it's a mistake to think that you can outwit nature by being better adapted. And often it's a sheer chance is some of the thinking now that's going on as to when catastrophic events hit planet earth and the climate changes—whether a species can or cannot survive.

NARRATOR:
AS SCIENTISTS WORK TO ANSWER VEXING QUESTIONS ABOUT MASS EXTINCTIONS, EVOLUTION, AND THE ORIGINS OF LIFE, THEY TURN THEIR

ATTENTION TO THE RECORDS LEFT BEHIND BY THE PRIMITIVE LIFE FORMS WHICH AT ONE TIME POPULATED EARLY EARTH.

J. WILLIAM SCHOPF, Ph.D., UCLA:
When Charles Darwin wrote "On the Origin of Species" in 1859, he was worried about his theory of evolution because he only had fossil records going back to roughly half a billion years ago. Now we know the earth is four and a half billion years old. So there was four billion years of missing fossil records. Darwin asked the question and it sat there for 100 years, until the mid 1960's, when for the first time microscopic fossils were discovered in old rocks. And since that time, from 1965 to today, the fossil record has been moved back, first to about a billion years and then a billion and a half to two billion years, to three billions years, now back to three and a half billion years.

We do have rocks that are 3.5 billion years old that seem to contain remnants of simple organisms that look very much like the photosynthetic organisms that exist in the ocean today. This is really exciting, because here we have in the rock record evidence that not only has life developed…on the earth, but it's evolved to the point that you have some sort of cellular organism on the earth at 3.5 billion years ago.

The oldest fossils known…come from three places. Two in Northwestern Western Australia and one in South Africa. And those three deposits are pretty much about the same age. That is, they are…about 3.4 to 3.5 billion years in age. The oldest one of those is called the Apex-Chert, and it comes from Northwestern Western Australia.

NARRATOR:
ANALYZING ANCIENT MICROSCOPIC FOSSILS IS CHALLENGING, NOT ONLY DUE TO THE AGE OF THE FOSSILS, BUT BECAUSE OF THEIR SIZE.

They're smaller than human hair. They're a lot smaller than human hair. These are bacteria—they're too small to see, and it's only been in the last, actually, 18 months now—the last couple of years—that there's a new technique called laser Raman Spectroscopy that permits us to look at the chemistry of these individual little cells. And this is work I've done with a group from the University of Alabama at Birmingham, and they have a beautiful instrument there that permits you—you shine a laser beam onto a specimen, and some of the energy, just a little bit of the energy, in that laser beam, is absorbed by the specimen and changes the light. And then you measure the changed light. And the measurement of that changed light tells you what the stuff is made out of. And it turns out, my goodness gracious, it is made out of organic matter. And so we can image. We can make chemical maps, chemical images, of these tiny little fossils now, and show exactly where the organic matter is and where it is not. And sure enough, it's sitting right in the fossils. They are three-dimensional and they have more or less the same sorts of shapes that they had when they were alive. And this helps us a whole lot, because we can then compare them in some detail to organisms that live today.

NARRATOR:
OF COURSE, AS WITH MOST SCIENTIFIC RESEARCH, NOT EVERYONE INTERPRETS THE DATA IN THE SAME WAY.

BADA:
With any of this kind of research, there are others who would disagree with…the interpretation that these little structures are derived from living entities, and would suggest that they're simply geofacts—artifacts that are developed simply by natural geochemical processes. And so this early history of the planet is very much obscured by all of these problems with the rock record.

NARRATOR:
EVEN IF THE ROCK RECORD DOES PROVE THAT THERE WAS LIFE ON EARTH 3.5 BILLION YEARS AGO, IT PROBABLY CAN'T TELL US MUCH ABOUT WHAT HAPPENED PRIOR TO THAT TIME, WHICH IS WHEN MANY SCIENTISTS BELIEVE THAT LIFE ON THIS PLANET ACTUALLY BEGAN.

GERALD JOYCE, Ph.D., M.D., The Scripps Research Institute:
The beginning, remember, is a molecular phase where Darwinian evolution was occurring, but not in an organismal sense, but rather in a sort of bag of—or maybe not even a bag, maybe just a local environment of chemicals. And if those chemicals were based on RNA, for example, you know, they'd be gone in the blink of the eye. I mean, gone in 10,000 years. So the fossil record does take us remarkably far back. Both direct and indirect fossil evidence puts life back to 3.5, 3.55 billion years before the present. But it's felt that the time of the origins of life was more like 4.0, maybe 4.2 billion years before present. And I'm afraid we're not going to expect to see—at least fossils in the traditional sense—that take us all the way back. But then I think we've got to think more generally about what is meant by a fossil. If a fossil is evidence of a prior life form, it doesn't necessarily have to be the kind of thing that you would brush off of a rock and outline with a toothbrush, and so on. There are fossils in the heritage of living organisms. In the molecules that are in organisms today, encoded is the history of their past, because each new generation builds upon the past generation.

NARRATOR:
AS SCIENTISTS CONTINUE TO GRAPPLE WITH BASIC QUESTIONS ABOUT THE ORIGINS OF LIFE, SOME HAVE ASKED, "COULD THE WHOLE THING EVER HAPPEN AGAIN, JUST AS IT DID FOUR-PLUS BILLION YEARS AGO? COULD THE ORIGINAL SPARK OF LIFE THAT TRIGGERED THE ENTIRE PROCESS SOMEHOW REOCCUR?"

TOM GARRISON, Ph.D., Orange Coast College:
We wonder whether biosynthesis could occur a second time on the earth. We know it occurred once and all the living things that we see on the earth are so similar in their basic biochemistry that we have every reason to believe, perfectly logical to understand, that there was a single instance of the origin of life on the earth, and all the living things

on the earth evolved from those chemical processes way back then. Could it happen again? No.

JEFF BADA, Ph.D., Scripps Institution of Oceanography, UCSD:
Once you have life in place, this is an incredibly efficient, self-sustaining system. It replicates itself, it consumes ingredients from the environment to make its—to use as constituents, and it's extremely competitive. Anything else that's trying to evolve the ability to replicate itself would just be out-competed. And so the possibility that you could have the origin of life take place after you already have life is very remote, simply because life would simply consume anything that was trying to compete with it.

NARRATOR:
AND SO IN A LITTLE MORE THAN FOUR BILLION YEARS, PLANET EARTH HAS NUMBERED AMONG ITS INHABITANTS EVERYTHING FROM MICROSCOPIC, EXTRAORDINARILY SIMPLE ORGANISMS…TO MANKIND, A SPECIES PERHAPS UNIQUE IN ITS ABILITIES, INCLUDING THE CAPACITY TO DESTROY THE VERY PLACE IN WHICH IT WAS BROUGHT TO LIFE. THIS VAST AND DIVERSE ARRAY OF ORGANISMS SHARE MUCH IN COMMON—CHEMICALS, PROTEINS, AMINO-ACIDS—THE VERY BUILDING BLOCKS OF LIFE, ALONG WITH PERHAPS A DOSE OF MYSTERY THAT SCIENCE MAY NEVER BE ABLE TO FULLY EXPLAIN.

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