OPUNTIA

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ISSN 1183-2703 **October 2007**

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THE ORIGIN OF LIFE: PART 1

by Dale Speirs

Introduction.

The origin of life is a popular topic that allows one to speculate at length without annoying facts getting in the way. The oldest known fossils are 3.8 billion years old, but are already organized cellular structures. The possibility is very low of anyone finding and proving beyond a reasonable doubt anything older that is obviously proto-life. Most discussion on the origin of life is therefore confined to thinking up and demonstrating chemical reactions that are self-sustaining and capable of reproducing themselves. The problem is not so much finding such chemical reactions, but to bridge the gap between them and organized cells. There are an astonishing number of chemical reactions which can self-replicate using simpler atoms or molecules to build bigger ones, known as auto-catalytic reactions.

The existence of life on Earth, often under extreme conditions such as hydrothermal vents or in deep rocks, strongly suggests that if it happened here then it could happen elsewhere in the universe [10, 28]. What should be emphasized is that there is a difference between life per se and sentient life. It seems highly probable, almost a certainty, that microbes and primitive multicellular life forms exist elsewhere in the universe in large numbers. There is a considerably lower probability that intelligent life on the order of a cat, dolphin, or dog could exist. The probability of sentient life able to develop significant technology and go into space is undecided with our present knowledge, and possibly as low as one species per many galaxies. That route, however, leads to exobiology, which is off topic for this essay and will not be considered further except briefly in the matter of panspermia.

Panspermia: Are We Aliens?

Panspermia is the idea that life did not originate on Earth but was introduced from space. This would short-circuit any discussion of how Earth went from chemical systems to cells, but would be even more difficult to prove. It is not as ridiculous as first seems, since we know from practical experience with spacecraft that bacterial spores can survive vacuum and minor radiation. A 1990s study by the European Space Agency lofted spores of *Bacillus subtilis* aboard a Russian satellite [5]. The spores exposed directly to space or behind a thin film of clay did not survive two weeks. Spores inside pellets of clay, soil, or rock only a few centimetres in diameter survived.

Another study tested bacterial spores in an ultracentrifuge and by firing them in capsules from a rifle [9]. This simulated the G forces that bacteria would experience on being ejected from a planet by some cause such as a major meteorite strike or a supervolcano. The bacteria survived such forces.

It is known that bacteria can live in deep rocks below the Earth's surface, so it is plausible that they could survive inside a meteorite that made it to the Earth's surface without too much internal heating. From there, everything would be consistent with the evolution of life radiating out from one point and using only a single genetic system, the RNA/protein/DNA world. The difficulty with panspermia is determining how the panspermic life originated elsewhere and on what planet. It therefore does not solve the problem, but only makes it more difficult.

From the zero-probability group, except to conspiracy theorists, there is the possibility that aliens visited the Earth 4 gigayears ago and we are descended from their skin bacteria. There is also a science fiction story about a time traveller who wants to find out when life began. He goes back in time but finds only a sterile planet. On his way back to the time machine, he drops a half-eaten food bar into the water and unknowingly contaminates the sea with bacterial life [15].

Basic Principles.

Scientists have been able to establish some basic principles about the origin of life on Earth because we know the end point is ourselves, and can thus work backward from present-day life. We know that any origin point must lead inevitably to liquid water and organic polymers, which are the basis for all life today. Water is the medium for chemical reactions in cells. The most important organic polymers are nucleic acids and proteins. Nucleic acids make up our genetic codes in chromosomes. Proteins are the molecules that actually do things, such as building cell components or generating chemical reactions.

The Earth is greater than 4.5 billion years old. Just exactly how old is not known for certain, but that number is the age of the oldest known rocks. Its first 500 to 700 megayears of existence were occupied in mopping up all the orbital debris in its neighbourhood, leaving it in a continual molten state from all the impacts. Continents and oceans did not develop any earlier than about 4.4 to 4.0 gigayears ago [16]. The frequent large impacts heated any oceans over 100° C, past the boiling point. This put any life that developed through bottlenecks that screened out everything but hyperthermophiles. Development of photosynthesis later allowed life to escape into cooler habitats as the planet cooled down. Silicon isotope studies have shown the oceans were 70° C about 3.5 gigayears ago and down to 20° C about 800 million years ago [14]. By 3.5 gigayears ago, most of the modern biochemical pathways that all species share had evolved and were global [11, 12]. That date is the age of the oldest known fossils, which were microbes. Bacterial mats dated at 3.2 gigayears old are known from South African deposits [58]. These mats stabilized the ocean sediments and reduced erosion, thus being one of the earliest known effects of life on the Earth.

After the final cooling of Earth from its molten state, water and simple organic compounds such as methane (natural gas) appeared. From there the chemicals reacted to build up larger molecules. Some of those larger molecules had catalytic ability, that is, the ability to generate new chemical reactions that would not otherwise occur. Since we exist, we know for a fact that some of the catalytic molecules developed the ability to assemble copies of themselves. Such molecules would soon predominate over other organic molecules that relied on external physical processes to exist.

The original autocatalytic molecules were probably inefficient and did not survive, but as all the variations played out, the more efficient autocatalytic molecules would win out. Eventually this primitive molecular evolution produced RNA, proteins, and DNA, and from there it was a short step to cells [1]. The original autocatalytic molecules were simple, but gradually evolved into more complex molecules capable of functioning even in times of resource scarcity, as opposed to straightforward chemical reactions which shut down when they run out of feedstock [59].

Which System?

There were several different types of chemical reaction systems arising, of which the RNA/protein/DNA system trumped all the others because the Earth settled down into an environment which did not favour the others [2]. These systems, called autocatalytic networks, were in competition with each other and each not only reproduced themselves from raw chemicals but generated their own stability [4]. These autocatalytic networks can be thought of as chemical ecosystems. A newborn autocatalytic system would spread exponentially as long as its source of supply was abundant [68]. Once it ran into limited supplies, its growth would slow down or stop. If two or more autocatalytic networks used the same nutrient sources, the most efficient system would eventually prevail.

If the Earth's chemistry changed, as it did several times in its early history, an autocatalytic system might find itself engineered out of existence because its feedstock was no longer available. Chemicals became interlocked in chain systems when the by-product or end product of one chemical was the starting point for another reaction. For example, if chemical A was the substrate for chemical B, which in turn was essential for chemical C, then the three would tend to become attracted to each other and form the chain A-B-C [90]. Many such chains could have existed, but only a few would have ever amounted to anything. Evolution acted as a filter, and screened out chain reactions which were not self-copying, or needed something too exotic to survive.

The first self-replicating molecules in autocatalytic networks had to face problems with mutations. A mutation is an error in the copy of a molecule. If it is a fatal error, that molecule never reproduces. If it is a beneficial error, improving the efficiency of the molecule, then it must be stabilized and not wiped out by a random fluctuation in the environment. In an infinite environment, fluctuations will wipe out the molecules sooner or later regardless of their efficiency in reproducing. Fortunately the Earth does not have any infinite environments; there were safe havens everywhere for life to weather out any storms. (That changed in the last century with the rise of industrial humans; we now pollute every square centimetre of Earth with our chemicals.) The mutation rate therefore eventually favours the efficient molecule, and autocatalytic networks can develop until they are robust enough to survive [6].

Another problem the earliest autocatalytic networks had to face was spontaneous decay. Molecules that are reactive, and thus favoured for autocatalytic networks, have a shorter lifespan than ordinary molecules. This is not a problem if the rate of creation stays ahead of the rate of spontaneous decay. In the long run, an extended life for an autocatalytic molecule is favoured by natural selection, so the short-lived molecules would be swamped out by longer-lived molecules. This effect pushed evolution towards an autocatalytic network that had a metabolic system (since molecules that do nothing are not life), a genetic system (to preserve the autocatalytic network over the long run), and a boundary (cell membrane, about which more later) [71].

The nucleic acids DNA and RNA prevailed. One reason appears to be the fact that they have parity codes [7]. A parity code is a self-checking code that reduces errors within each gene. In fact, genetic abnormalities in humans or other organisms are mostly due to the presence or absence of genes rather than an error within the actual gene itself. Genetic diseases are usually a result of a missing gene that should be synthesizing something useful, or an extra gene that is synthesizing something that it shouldn't. Using modern advances in computer technology acting as a guide, the RNA/DNA system can be considered as a 4-digit binary system storing information [8].

One peculiarity of many organic molecules is that they have handedness. With exactly the same chemical formula, the molecule can have two different shapes that bend in opposite directions and are mirror images of each other. These molecules are called isomers. An analogy is your hands, which are mirror images of each other even though they have the same structure. It happens to be the case that left-handed amino acids predominate on Earth, and our genetic biology is based on this handedness. Left-handed amino acids predominate because they are slightly more stable than right-handed amino acids [31]. In a quiet primitive Earth ocean, it could have been remotely possible that two sets of life evolved, one with left-handed and the other with right-handed organic chemicals. This is a low order probability however, because any kind of turbulence would start the two ecosystems mixing, and the left-handed system would have defeated the right-handed system [32]. Another reason is that under evaporative conditions, one isomer precipitates out of solution faster than the other. From the amino acid point of view, the left-handed ones stay in solution longer and thus survive in greater concentration than their mirror images. It takes as few as two evaporative cycles to convert an organic soup into 90% left-handed molecules [33].

The earliest form of natural selection, even as life was still being born, was thus the struggle between left- and right-handed molecules. Our biology to this day depends on the handedness of our molecules. There is not, however, any standard of handedness in genetic molecules. DNA is actually a right-handed double helix, and is extremely rarely found as a left-handed spiral. The main reason for the variance is that whichever form of a molecule is the more stable is the one that will ultimately prevail.

RNA World Versus Protein World.

DNA is obviously a derived molecule from RNA, but RNA and proteins are so interlinked functionally that there has been considerable debate to which originated first [43]. Proteins can self-assemble from amino acids into short pieces called oligons, but RNA is needed as a template to assemble larger proteins. The general consensus currently supports what is called "the RNA World" hypothesis.

One item to note in passing is that viruses are a descended degenerate form of the RNA/DNA world, not an ancestor. A virus is a package of RNA or DNA surrounded by a protective structure (or naked, in the case of some species that only propagate by exchange of bodily fluids). It is basically a piece of chromosome run wild [64]. Viruses cannot be considered as ancestral to life.

The argument of the Protein World hypothesis is that amino acids paired off to make codes in protein form, and then RNA came later as a backup copy device [56]. Proteins can organize in hierarchical patterns and develop scale-free networks [83]. This would enable the transmission of information from one generation of proteins to the next, that is, genetics. From there, both proteins and RNA became more elaborated. A variation on this is that iron-nickel sulphides, something common in the early Earth, catalyze peptide formation, a type of protein sub-unit.
The peptides later break down into urea and amino acids [57]. Another possibility is the triose-ammonia reaction, triose being a simple type of sugar [89]. Under anaerobic conditions, with no oxygen, these two substances set off catalytic reactions.

DNA did not come until after RNA, since it is a derived structure. Its advantage is that it is a larger molecule that can grow bigger, has more stability, and hold more genetic information than RNA [69]. Modern types of proteins that have evolved since the early days require more genetic information to assemble than a given RNA molecule can hold.

Engines Of Creation.

There are a multiplicity of ways to synthesize amino acids in simulated primitive environments. The early Earth was not a nice place to live for humans, mainly because there was no oxygen atmosphere. Every potential habitat suffered strong blasts of radiation (since there was no ozone layer), continual lightning storms, and shock waves propagating through the atmosphere from meteorite impacts and violent vulcanism. Strangely enough, this would have helped synthesize amino acids, the building blocks of proteins, as the large energy inputs would speed up chemical reactions [3].

This brings up the point that the origin of life depended on a balance of energy. On the one hand, there had to be sufficient energy to allow chemical reactions to proceed, not only at the normal rate but faster than usual to allow for complex molecule formation. On the other hand, too much energy would tear apart the prebiotic chemicals before they got going. Earth was more radioactive in those days, and fossil natural fission reactors are known from Africa and Canada. The deep rock radioactivity supplied as much energy as the sun, and would have helped catalyze chemical reactions [30].

It appears that one reason Earth was blanketed by life, and not Mars or Venus, is because this planet is tectonically active [77]. Continents float about the surface, bash into each other, and are subsumed below the surface when one tectonic plate slides below another. This constantly re-processes the elements and brings them back up to the surface again in useable form. This is particularly important for phosphorous, which is the energy source of cellular metabolism.

Without tectonics, most of the essential elements would eventually be locked into the ocean sediments and volcanoes would run dry of magma. (The reason why so many people insist on living near volcanoes is that the weathered ash makes the most fertile soil in the world for farmers.)

Were We Shaped Out Of Common Clay?

Originally it was thought that life must have evolved in some sort of organic soup (or, as Charles Darwin put it, a "warm little pond"), but recent decades have brought more and more papers suggesting that life first evolved on some sort of substrate, the most popular candidate being grains of clay. The various substrates would a<u>d</u>sorb (collect on their surface, as opposed to a<u>b</u>sorption, which is to collect within) the building blocks of life. Free-floating nucleic acids or proteins would be subject to being broken up as fast as they formed in the primordial soup, although their component parts, the nucleotides and amino acids respectively, are small enough that they could survive in the soup. If attached to a substrate for stability, nucleic acids and proteins then have a better chance to assemble into large molecules.

All life depends on phosphorous for energy storage and subsequent release. Precipitates from the organic soup may have provided a site for prebiotic reactions involving phosphorous known as phosphorylation [82]. By occurring together with other autocatalytic reactions, an assemblage of molecules could build up that would assist each other in surviving and reproducing.

Montmorillonite and kaolinite clays have been ubiquitous throughout Earth's history, and are formed by aqueous weathering of volcanic ash.

The thinking is that they would have provided a stable point of attachment for nucleic acids or proteins to build up their structures [18 to 20]. The chemicals are held close to the particles by electrically charged atoms or small molecules known as ions. The adsorption is mediated by sodium, calcium, or magnesium ions, which act as a bridge between the clay surface and the adsorbed organics [25]. Clay particles allow nucleotides, the building blocks of nucleic acids, to build up in chains called oligomers, which are partial lengths or sections of nucleic acids [24]. The clay particles act as catalysts by snatching nucleotides floating by and holding them firm onto the particle. Adsorption of nucleotides onto clay particles varies by the type of nucleotide, which would also have a bearing on which nucleotides ended up being the basis of the genetic code. In a similar manner, proteins can be built up from amino acids.

This process has been replicated in clay-lined pools with hot water, into which nucleotides and amino acids have been released [21]. The clay removed the organics from the water in a few minutes to a few hours, adsorbing them onto the particles. Modern enzymes, which are mostly proteins, have been found in modern lakes on clay sediments, still active and functioning despite the lack of protection by cells [23]. Laboratory tests have shown that nucleic acids on clay suffer less radiation damage than free-floating nucleic acids [17]. Another project demonstrated that if the number of cycles of fluctuating temperature and

moisture increase in frequency, then the clay particles produce peptides of greater length [61].

Other Substrates.

Clay has been the favoured substrate of study because of its abundance, but there are other possibilities. Pyrites, such as iron disulphide (fool's gold), are abundant and could have provided a reactive surface [27]. However, studies have shown that pyrites are a little too reactive and rapidly degrade RNA unless the pyrites are coated with lipids [62]. There is fossil evidence that by 3.47 gigayears ago there were life forms processing sulphates for energy [80], so the use of sulphur for metabolism is one of the oldest biotic processes on Earth. Impact craters from smaller, non-extinction level asteroids would have provided a diverse substrate with mixtures of metal sulphides, clays, hydrothermic deposits, and fracturing of rock to provide more surface area [26].

Chains of phosphate molecules, known as inorganic polyphosphates, could have provided a framework for organic molecules to assemble themselves on [84]. These are found in every cell today, and have high-energy bonds between the phosphates that provide cells with energy to operate. It would not be difficult for them to provide a strong evolutionary advantage upon which the modern structure of cells would develop.

Water-filled volcanic craters have been demonstrated to allow extremophiles to survive [47]. These are not erupting volcanoes, but dormant volcanoes with strong upwelling hot-water springs bringing up dissolved minerals from the vent, almost like Darwin's warm little pond. The microbes that survived in these vents, dated back to 3.49 gigayears ago, were chemautotrophs, getting their energy from chemical reactions in the hot water. One suggestion is that in or near volcanic gas vents there were catalytic metallic molecules which covered themselves with carbon while breaking apart gases for energy [50]. The carbon would then build itself into organic structures surrounding the inorganic compounds and the result would be self-sustaining autocatalytic protolife, which would then evolve through natural selection for greater energy efficiency.

Crystalline graphite has been shown to adsorb nucleic acids and amino acids in a coding-type process [22]. Graphite, which is pure carbon in sheet form, has been suggested to be all that remains of the earliest proto-life. This is a tempting idea because graphite is widespread in ancient 3 to 4 gigayear old deposits, which is consistent with a global spread of microbes. Alas, the idea has since been repudiated by demonstrating that it can form by non-organic processes [48 and 49].

Layered double hydroxide crystals with internal voids that could serve as information storage have been proposed [63]. Non-asymmetric crystals such as these could produce original and copy, as well as exist in chiral or handedness form to provide further means of coding. The catch would be in the transition from crystals to an RNA World.

Earth's modern atmosphere is an ecosystem in itself. Microscopic particles and water droplets circulate far above the clouds, as well as organic matter and chemicals. On this basis, it has been suggested that single-cell life could have originated in the atmosphere [29]. Given that the primitive Earth atmosphere was a high-energy environment, it is doubtful that proto-life could have survived long enough to propagate. It is certainly possible that simple organic precursor chemicals could have been generated in the atmosphere by lightning and rained down onto the surface, but complex molecules would have no protection in such a turbulent ecosystem.

Another hypothesis is that microscopic bubbles constantly floating in the ocean will develop surface films at their water-air interface [53]. These bubbles are not the visible size that float up to the surface and pop, but bacteria-size bubbles that can exist indefinitely and circulate in the water. The film of accumulated organic molecules could provide the bubbles with a membrane, and when an autocatalytic molecule gets inside, the result would be a proto-life form.

After the Earth solidified and cooled down (relatively speaking), it was subject to wild climatic swings before the atmosphere finally stabilized into an oxygen/nitrogen mix. There were times of runaway heating, the greenhouse effect, and of runaway glaciation, the Snowball Earth effect, when the entire planet was covered by ice. It has been suggested that during the earlier Snowball Earth periods that life could have evolved using ice as a substrate [85 to 87]. Alternate freezing and thawing underneath the ice sheets where the ice slid over hot spots such as springs or volcanic vents would allow prebiotic autocatalytic networks to form, possibly even the synthesis of RNA sub-units.

The farthest off-the-wall proposal was a single substance origin, purely of one type of atom in crystalline form [60]. Atoms come in different isotopes, or weights, depending on how many neutrons they have in their nucleus. Isotopes can be naturally sorted because of the weight difference and minuscule differences in reactivity. A genetic code might have developed in porous crystals using only isotopes of one atom. These isotopic patterns might then react with other atoms or molecules as a template, and build up some secondary form of organic chemical chains, which in turn would might lead to an RNA/protein world. A good idea for a science fiction story, but not very plausible.

[to be continued]

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LETTERS TO THE EDITOR
[Editor's remarks in square brackets.]

FROM: Lloyd Penney 2007-01-31
1706 - 24 Eva Road
Etobicoke, Ontario M9C 2B2

[Re: Canadian postal codes] My wife Yvonne worked for Canada Post many moons ago in the postal code department. She was the one who came up with the bilingual listing of streets and their French equivalents. Some postal codes are not used because of confusion. One was an Alberta code, T0K 1Y0. Lots of mail destined for that village wound up in Japan.

[That postal code is still used for the village of Aetna in southwestern Alberta. Although its post office closed several years ago, it is still a rural route via Cardston (named after the SF writer's grandfather), and the residents still use the code.]

[Re: SF conventions] Every few years, new people on the committee are forced to re-invent the square wheel. I have tried asking people to write down the procedures they followed but people just won't do it, and they leave their successors to figure it out by themselves.

[It isn't just convention planners. Where I work, there has been a major turnover in staff because of Baby Boomer retirements and people leaving to work for oil companies. As a result, the quality of park maintenance has declined because there is no one left to train the new staff. We have big binders full of job procedures, but few look at them, and even if they did, there are a lot of unwritten procedures that only come with experience.]

FROM: A. Langley Searles 2007-03-20
48 Highland Circle
Bronxville, New York 10708-5909

[Re: Permian mass extinction] My feeling is that the next mass extinction on this planet, assuming it would be caused by a colliding asteroid, is going to be different from past ones because there's more flammable stuff around than there ever has been: coal, petroleum, natural gas, forests, and man-made structures. A very small asteroid, one that might do merely local damage, could set afire the Montana coal fields, Saudi oil fields, or the Athabasca Tar Sands.

Such fires couldn't be controlled but would have to burn themselves out. Is there enough oxygen in the atmosphere to burn everything? If there isn't, that's the end of all mammalian life on the planet right there.

[Underground deposits would not be affected. The proof of this is that many coal and oil deposits are up to 200 megayears old, yet they were not ignited by the Cretaceous asteroid impact that killed off the dinosaurs of North America about 65 megayears ago. The Athabasca Tar Sands are underground oilsands that were freshly exposed to the surface after the last continental ice sheets scraped off most of the overburden about 10,000 years ago. They do not burn easily, which is why it costs $30 a barrel to melt them out of the sands.]

Another thought: maybe humans are doing themselves a favour by using up all the coal and oil and spreading the global warming over a few centuries, instead of risking it happening all at once.

[It depends where you live, of course. I'm alright in Calgary, which is a kilometre above sea level. I don't know the altitude of Bronxville, but if your house is only a few metres above sea level, then you may have problems damp-proofing the basement.]

FROM: Kris Mininger 2007-??-??
Calle Obispo 4 bajo
Plasencia 10600, Caceres, Spain

[Re: Permian mass extinctions] I almost fell off my chair in shock when I read about the lava deposits in eastern Siberia that go down to 6.5 kilometres in depth. How do they measure that? Tsunamis of lava; I can think of nothing that would be more terrifying.

[Geological deposits are almost always composed of thinner layers called strata, of varying thickness and texture. The lava deposits have since been tilted at an angle by tectonic forces, which expose the strata like a layer cake. It is then a matter of traveling along the exposures and mapping each stratum as it appears above the surface. From one end to the other, the strata add up to about 6.5 kilometres depth. This is a common method for mapping coal and mineral deposits.]

I Also Heard From: Franz Zrilich, John Held Jr, Chester Cuthbert, Anna Banana, Peter Netmail

SEEN IN THE LITERATURE
noticed by Dale Speirs

Van Flandern, T. (2007) **The challenge of the exploded planet hypothesis.** INTERNATIONAL JOURNAL OF ASTROBIOLOGY 6:185-197

"*The hypothesis of the explosion of a number of planets and moons of our Solar System during its 4.6-billion-year history is in excellent accord with all known observational constraints, even without adjustable parameters or ad hoc helper hypotheses. The successful predictions include: (1) satellites of asteroids; (2) satellites of comets; (3) salt water in meteorites; (4) 'roll marks' leading to boulders on asteroids; (5) the time and peak rate of the 1999 Leonid meteor storm; (6) explosion signatures for asteroids; (7) the strongly spiked energy parameter for new comets; (8) the distribution of black material on slowly rotating airless bodies; (9) splitting velocities of comets; (10) the asteroid-like nature of Deep Impact target Comet Tempel 1; and (11) the presence of high-formation-temperature minerals in the Stardust comet dust sample return. Among the many important corollaries are these. (a) Perhaps as many as six former planets of our Solar System have exploded over its 4.6-billion-year history. (b) In particular, Mars is not an original planet, but a former moon of an exploded planet. (c) As a major player in Solar System evolution, the exploded planet scenario must be considered as a likely propagation vehicle for the spread of biogenic organisms.*"

Bottke, W.F., et al (2007) **An asteroid breakup 160 Myr ago as the probable source of the K/T impactor.** NATURE 449:48-53

"*The terrestrial and lunar cratering rate is often assumed to have been nearly constant over the past 3 Gyr. Different lines of evidence, however, suggest that the impact flux from kilometre-sized bodies increased by at least a factor of two over the long-term average during the past 100 Myr. Here we argue that this apparent surge was triggered by the catastrophic disruption of the parent body of the asteroid Baptistina, which we infer was a 170-km-diameter body that broke up 190-140 Myr ago in the inner main asteroid belt. Fragments produced by the collision were slowly delivered by dynamical processes to orbits where they could strike the terrestrial planets. We find that this asteroid shower is the most likely source (>90 per cent probability) of the Chicxulub impactor that produced the Cretaceous/Tertiary (K/T) mass extinction event 65 Myr ago.*"

Speirs: The K/T impactor is the asteroid smash that triggered the extinction of the dinosaurs.