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Biocosmology: a New Science of the Big Picture

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Abstract: Abstract: It is argued that a cross-disciplinary approach is required if we want to understand how life forms evolved from non-life forms. The new science of cosmobiology is described as a big picture form of astrobiology and an explanation given of how its focus on the expansion and the chemical evolution of the Universe can give us the broadest context for understanding other life that may exist in the Universe.

Keywords: Cosmobiology, astrobiology, evolution, life.

The opposability of your thumb clasping this paper testifies to your arboreal past. Your thumb is made of water, protein and bone, testifying to your status as a terrestrial life form. Water protein and bone are made of hydrogen, oxygen, carbon, nitrogen and calcium, which are in turn made up of protons, neutrons and electrons. Thus, to understand how your thumb came to be, we need to know how sub-atomic particles came together to form atoms, how atoms came together to form molecules, how molecules evolved into life forms and how life forms evolved into creatures that climbed trees and grasped things. We need to know at least the basics of physics, astronomy, chemistry, biology and evolution. No one of these sciences can give us a satisfying picture of the origin and evolution of thumbs, for a thumb (just like every other part of the Universe) has a 14 billion year history and contains no boundaries where its physics ends and its chemistry begins, or where its chemistry ends and its biology begins.

Despite this natural undividedness of all parts of the Universe, universities are partitioned into physics, chemistry and biology departments full of specialists. This intellectual balkanization has a price. It encourages the separation of the Universe into living things studied by biological scientists and non-living things studied by physical scientists. It fosters the pretense that there is a sharp division between the two that should not be crossed. This assumed division thwarts the understanding of the many fundamental connections that exist between the living and the non-living parts of the Universe and it undermines our ability to understand the origin of life and the important transition from non-living to living things.

It is beginning to be recognized that to address the issue of the origin of life and whether we are alone in the Universe, the strong traditional boundary between the life sciences and physical sciences will have to come down. As it does, astrobiologists enthusiastically clamor over the fallen walls — erstwhile reductionistic researchers embracing a more synthetic approach. Astrobiology is a synthesis of astronomy and biology. An even broader and more synthetic approach to the study of the origin of life in the Universe is a combination of cosmology and biology: biocosmology. I believe biocosmology will give us many important insights as we struggle to produce a big picture understanding of how we (and our thumbs) came to exist in the Universe.

Biocosmology focuses on the cosmic evolution of the Universe on the largest spatial and temporal scales. It is a science that studies how the evolution of non-living things created the ingredients and the conditions for the emergence of life. As astronomers study the details of star formation, cosmologists put star formation in context by studying the evolution of star formation since the Big Bang. Biocosmology tries to identify the cosmic processes which over time have allowed biological creatures like ourselves to come into existence. One such cosmic process is the expansion and cooling of the Universe, as plotted in Figure 1.

Life as we know it is based on molecules; clumps of atoms that froze out of the cooling Universe when its temperature of the universe fell below molecular binding energies (Figure 1). Thus, the expansion and cooling of the Universe has been the most basic prerequisite for the origin of molecules and molecular life. However, life cannot be made out of the cooling hydrogen and helium produced in the Big Bang. Many generations of massive stars had to form and die before the ashes of nuclear fusion accumulated to contain enough oxygen, carbon, nitrogen, sulfur and phosphorus to produce watery environments and allow the chemical evolution of carbon molecules into hydrocarbons, carbohydrates and life.

Four elements make up more than 99% of the atoms in terrestrial life: hydrogen, oxygen, carbon and nitrogen. Add seven more elements to this mix (S, P, Cl, Na, Mg, K and Ca) and we have more than 99.99% of the atoms in terrestrial life. Of all these ingredients, only hydrogen was made in the Big Bang; the rest were produced in the hot fusing cauldrons of massive stars all over the Universe. Their ubiquity ensures that the ingredients for life are present throughout the Cosmos.

Water is one of the most essential ingredients for life and is one of the most abundant molecules in the universe. In fact, water is the most common triatomic molecule in the Universe. This makes sense since hydrogen is by far the most common element in the Universe and, after the inert noble gas helium, oxygen comes next in abundance. To be useful to life, H_2O must be a liquid, not ice or steam. To remain a liquid on the surface of a terrestrial planet, the planet should be orbiting a star in the circumstellar habitable zone.

There are many reasons to believe that terrestrial planets, broadly defined, in habitable zones are ubiquitous in the Universe (Lineweaver et al. 2003). For example, planets are formed in accretion disks and accretion disks are necessary ingredients in our best models of star formation. The latest observations and simulations are consistent with the possibility that rocky planets orbit the majority of stars.

Even if we accept that terrestrial planets are common, in order for life to emerge and evolve into something interesting, millions or even billions of years in a clement stable aqueous environment may be required. Supernovae are the required suppliers of O, C, N, S and P but if they explode nearby they can also extinguish life. Thus, there may be a Galactic Habitable Zone close enough to the debris of supernovae to enjoy a complex chemistry but far enough away from supernovae to enjoy a clement environment for the perhaps billions of years required for the biological evolution of interesting organisms (Lineweaver et al. 2004).

From the aqueous environment sketched in Figure 2, life emerged on Earth about 4 billion years ago and branched into the three domains shown at the top of Figure 2 and in Figure 3: *Eubacteria*, *Archaea* and *Eukarya*. We have many ideas about how life got started but none of them are compelling or complete. However, recent progress in molecular biology and genetics has allowed us to trace out the evolutionary tree of life on Earth, showing how all life forms are related to each other (Figure 3).

We do not know if such a tree of life exists on other terrestrial planets. However, we can use this tree to make better guesses about what forms of life we should expect elsewhere. For example, life forms at the root of this tree are the common ancestors of all life on Earth. They are simpler and less quirky than the life forms they evolved into and these simpler organisms therefore may be more representative of what we should expect to find at the base of alien trees of life. That is to say, as far as predicting aliens goes, the smart money is on hyperthermophilic bacteria, not vertebrates.

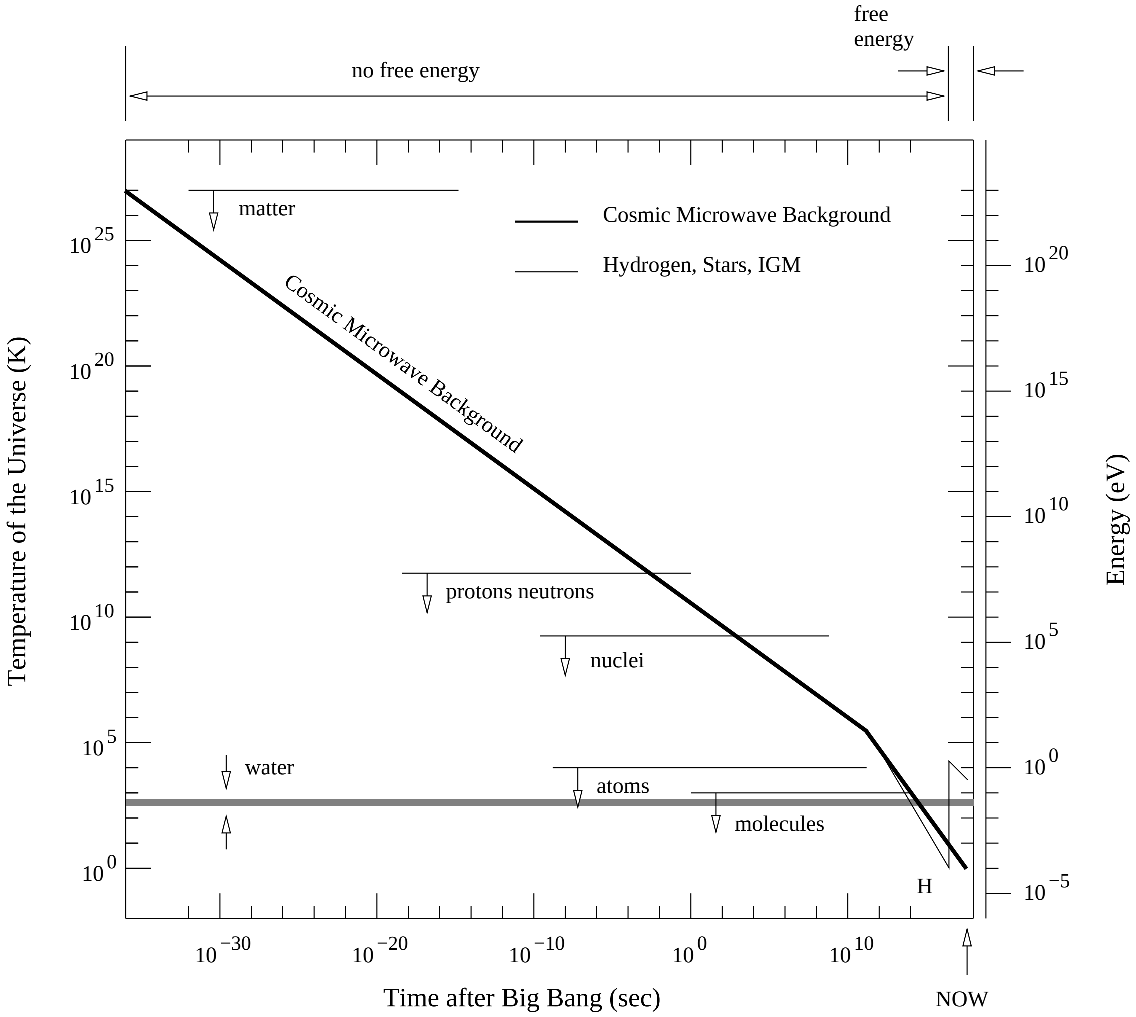

Figure 1. The most important thing one needs to know about cosmology is that the Universe used to be very hot and has been cooling down since its beginning. The sloping line labeled CMB is the temperature of the Cosmic Microwave Background, which is the temperature of the Universe. The molecules, atoms and subatomic particles that we now take for granted have not always existed. As the hot Big Bang cooled, matter came into existence probably about 10^{-33} seconds after the Big Bang. At a thousandth of a second after the Big Bang the quark-gluon plasma cooled and condensed into protons and neutrons. Within three minutes these particles had condensed into light nuclei. As the Universe continued to cool, atoms formed for the first time and as the atoms cooled below the binding energy of molecules, molecules were able to form. If the Big Bang had produced oxygen, water would have been able to form then, but water had to wait until stars formed and produced oxygen (see Lineweaver and Schwartzman 2004 for details).

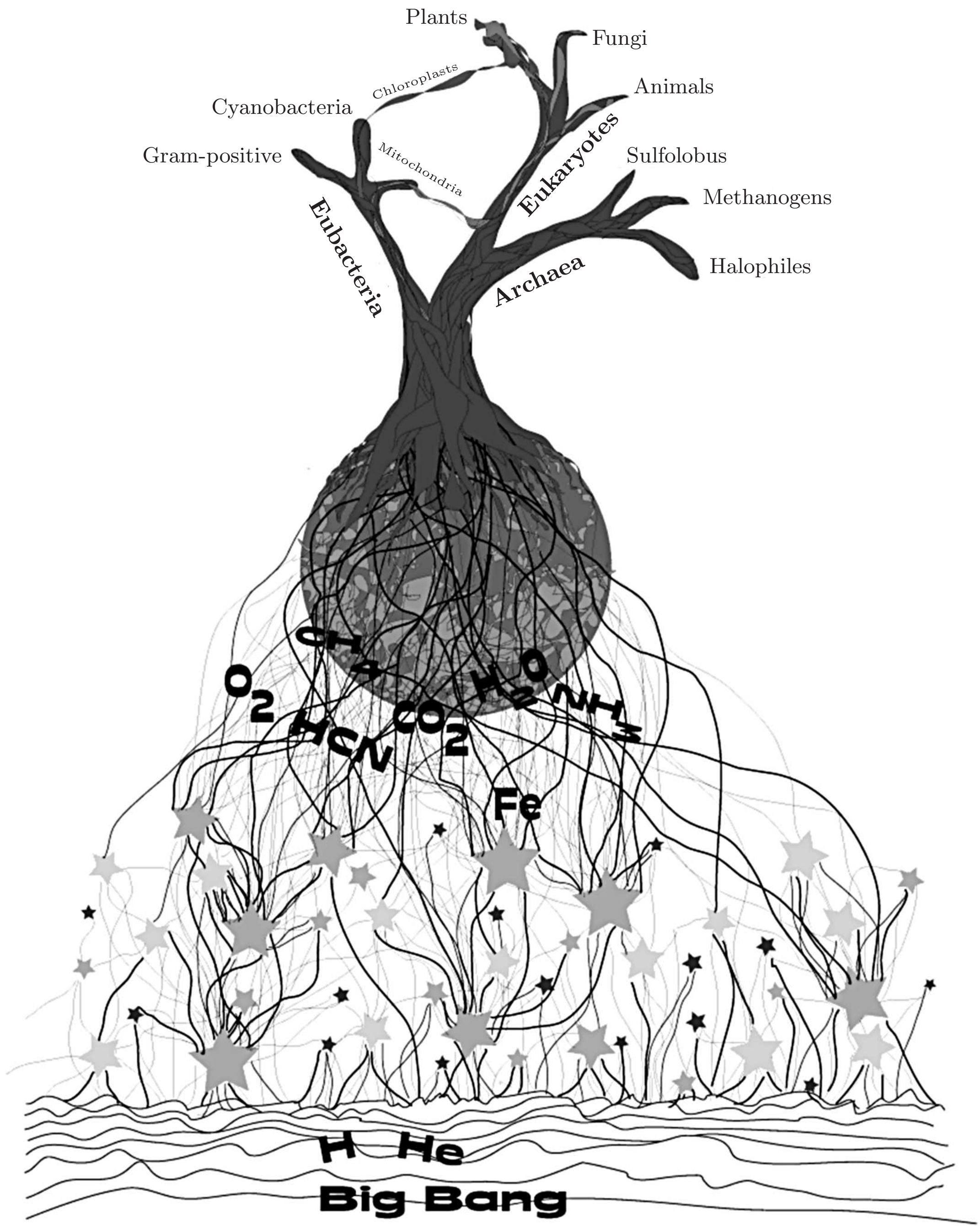

Figure 2. The history of the Universe since the big bang is summarized in this cartoon. The hot Big Bang (bottom) produced hydrogen and helium (H and He). Clouds of H and He gravitationally collapsed to form stars of various masses. The massive stars exploded after a few million years and spewed into interstellar space the ashes from the nuclei that had fused in their cores. After eight billion years of such reprocessing and accumulation, our Sun formed five billion years ago from a gravitationally collapsing cloud of molecular hydrogen contaminated by oxygen, carbon, nitrogen and other heavy elements. The Earth formed from this contamination in the accretion disk around the young Sun. As the Earth accreted, water was deposited on its surface by comets and water vapour outgassed from hot rocks, just as volcanoes do today.

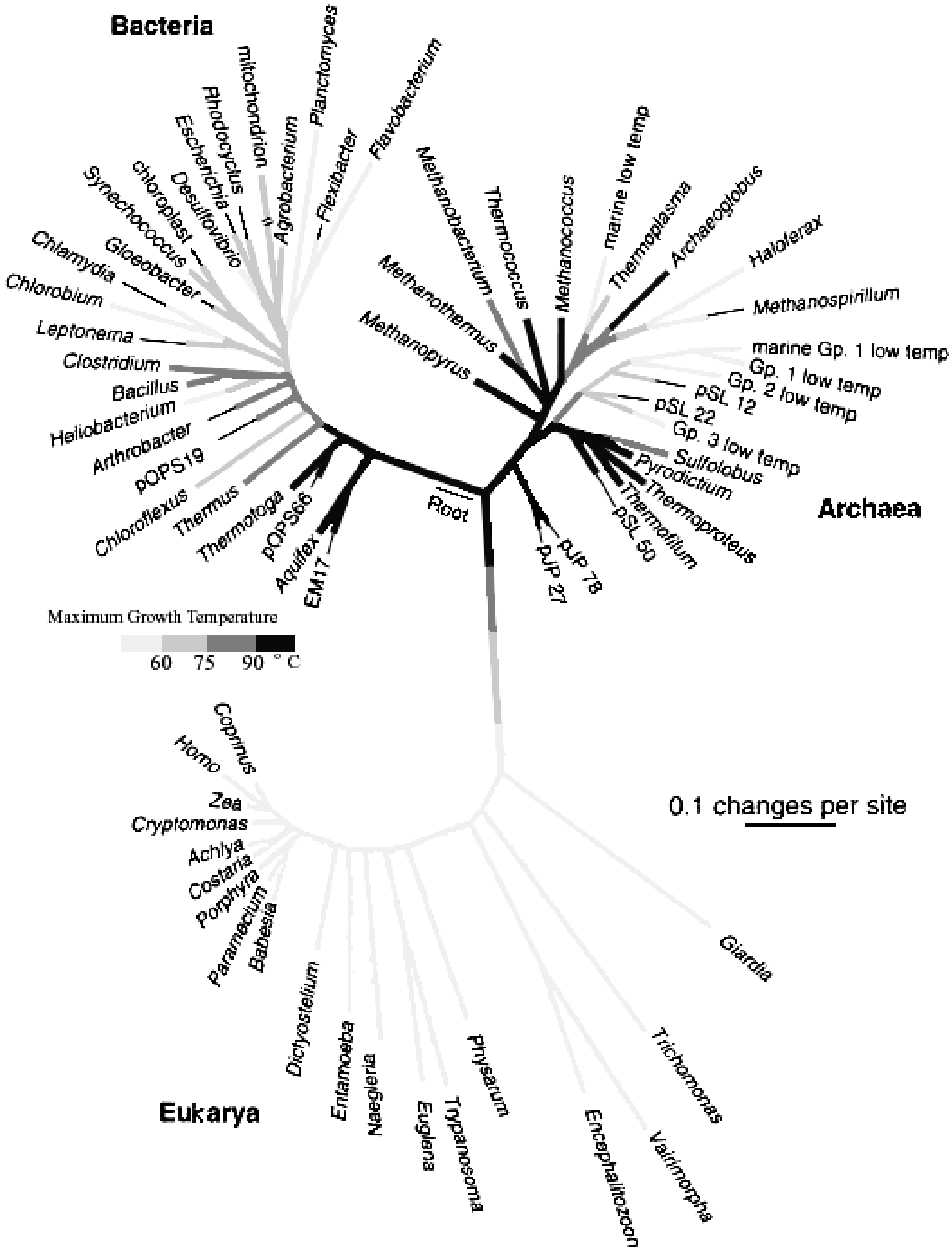

Figure 3. Phylogenetic tree of life on Earth based on 16S rRNA sequences. Life started as a hyperthermophilic *eubacteria* or *Archaea* and branched out (see Lineweaver and Schwartzman 2004 for details). Maximal growth temperatures have been used to assign a grey scale to the branches and thus to construct this biological thermometer on billion year time scales (see Pace 1997 for details concerning the construction of this tree).

Consider the two biocosmological facts (1) terrestrial biogenesis occurred rapidly and life formed on Earth soon after it was able to, and (2) terrestrial planets are not made of anything unique; life forms and planet Earth are made of the most common elements available in the Universe. These facts suggest that life may be common on terrestrial planets throughout the Universe (see Lineweaver & Davis 2002 for details).

Combining our knowledge of the cooling of the Universe and of the formation of stars and planets, and of the composition of those planets and the earliest forms of life on Earth is one example of how biocosmology brings together the study of life forms and cosmic processes to help us understand how we fit into the Universe and how we compare to other life forms that may inhabit the Universe.

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