PROCEEDINGS OF SCIENCE

From Big-Bang to Big Brains

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I suggest that many deep connections between astrophysical processes and the emergence and evolution of life in the universe are beginning to be revealed. The universe has changed dramatically over its history and so too have the conditions for life. The multi-frequency nature of cosmic sources has had and continues to have significant effects on the habitability of planetary surfaces. The first potentially habitable exoplanets will be characterized soon and these observations will shed light on the prospects for the discovery of extrasolar life. Most stars likely do not host complex life. Single-celled creatures might be inevitable on some planets under a wide range of conditions. However, multicellular life may not develop at all in many cases, due to extreme environments or catastrophe. Complex life probably requires hospitable conditions lasting billions of years, like we have enjoyed here on Earth.

The story of life on Earth is one of intense biosphere production that, for example, changed the chemical composition of the atmosphere and the oceans. Niches for oxygen-consuming life opened the way for animals. This may not be an easily crossed threshold. Evolution of life on Earth was punctuated by at least 5 major mass extinctions and many minor ones. The stresses placed on life by the geological and extraterrestrial environment and natural selection have honed members of the surviving species into beings well adapted to their environments. However, high intelligence is not at all an inevitable outcome of this process. 'Big brains', those capable of establishing a technological civilization, did not develop in the oceans of Earth, despite billions of years. Even then, big brains do not necessarily translate into ultimate success. Habitable conditions on every planet will eventually end. For life originating on a planet to succeed, intelligence and a technological civilization is needed to protect the planet's habitability. After 4.5 billion years, only now is life on Earth capable of developing protection against mass extinction by, for example, asteroid impact avoidance and contagious illness prevention. Without the development of science, any planetary civilization is doomed to tread water until the next mass extinction. While we may not expect to be communicating with extraterrestrials any time soon or even to find a planet with complex life, I am optimistic that soon the large subset of uninhabitable planets will begin to become characterized. In these brief comments, I summarize some connections between topics of modern astrophysics and life, especially so-called *life as we know it*. All of my attempts to characterize *life as we don't know it* have fallen flat.

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The universe is old but not infinitely so. Now, we can say with some certainty that life was not possible anywhere in the universe for a significant fraction of its history. In fact, there is a deep connection between cosmology, astrophysics, and life. When considering the processes that have clearly enabled life in the universe, especially to the development of big brains, all the tools of all the sciences must be employed. I briefly examine a few results here.

1. The Emergence of Structure

The development of the large scale structure of the universe is modeled as random fluctuations visible in maps of the Cosmic Microwave Background Radiation [1]. These fluctuations in temperature and density allowed concentrations of dark matter to form, grow, and become a network of matter stretching across the universe. In Figure 1, The Millennium Simulation predicts a piece of the large scale structure at modern times. This network connects the rich dense clusters of galaxies at nexus points of a vast web to the medium sized galaxy clusters through arteries. In the real universe, the center of the Virgo Supercluster is the "great attractor" dominating the gravitational potential of the local clusters of galaxies. The cosmic web ultimately stretches out to small clusters like the Local Group and out to the lower density regions of the cosmos. Figure 1 also illustrates the large scale distribution of life in the universe [2].

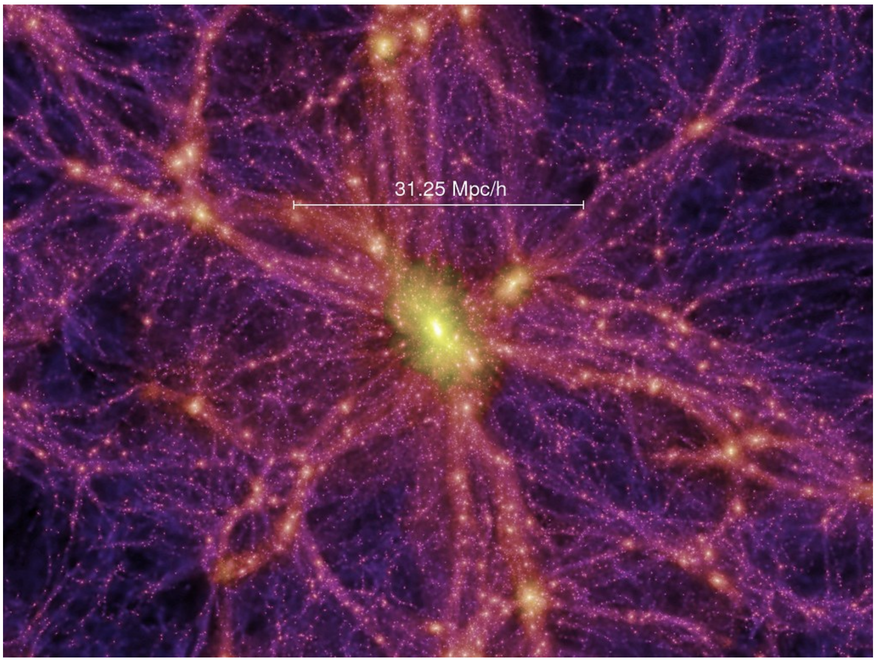

Figure 1: The Millennium Simulation of the large scale structure of the universe. Credit: The Virgo consortium, German Astrophysical Virtual Observatory

The universe is a violent and dangerous place. Mason and Biermann [2] suggest that the densest regions of galaxy clusters remain uninhabited by complex life as the result of extreme conditions from AGN activity, galaxy mergers, as well as high star formation, gamma-ray burst, and supernova rates. Low density regions containing low metallicity dwarf galaxies are also likely uninhabited. This concept is generalized as the Super-Galactic Habitable Zone [2].

2. The Elements for Life

The path from elementary particles through Big-Bang nucleosynthesis to the formation of galaxies, stars, simple molecules, and their incorporation into planets is a long and complex one. The first stars in the universe did not offer the first habitable environments around them. They did however fuse the first elements for life. The modern quest for life follows the mantra of astrobiology, namely to *follow the water.* Simple molecules may develop into organic molecules in suitable environments, from molecular clouds to protoplanetary disks. Critical to the emergence of life is the process of planet formation and details concerning the retention and delivery of water are key to the formation of a potentially habitable planet. Stars forming early in the life of a galaxy likely do not have enough, or the right kind, of elements. As far as we know, life sustaining planets need to form with significant quantities of iron, silicates, carbon, nitrogen, oxygen, and so on. Even radioactive elements benefit complex life because radioactivity maintains and prolongs the geologic lifetime of a planet. A planet with significantly less core radioactivity than Earth would loose the thermal gradient currently driving plate tectonics which is vital for the life-sustaining carbon-silicate cycle.

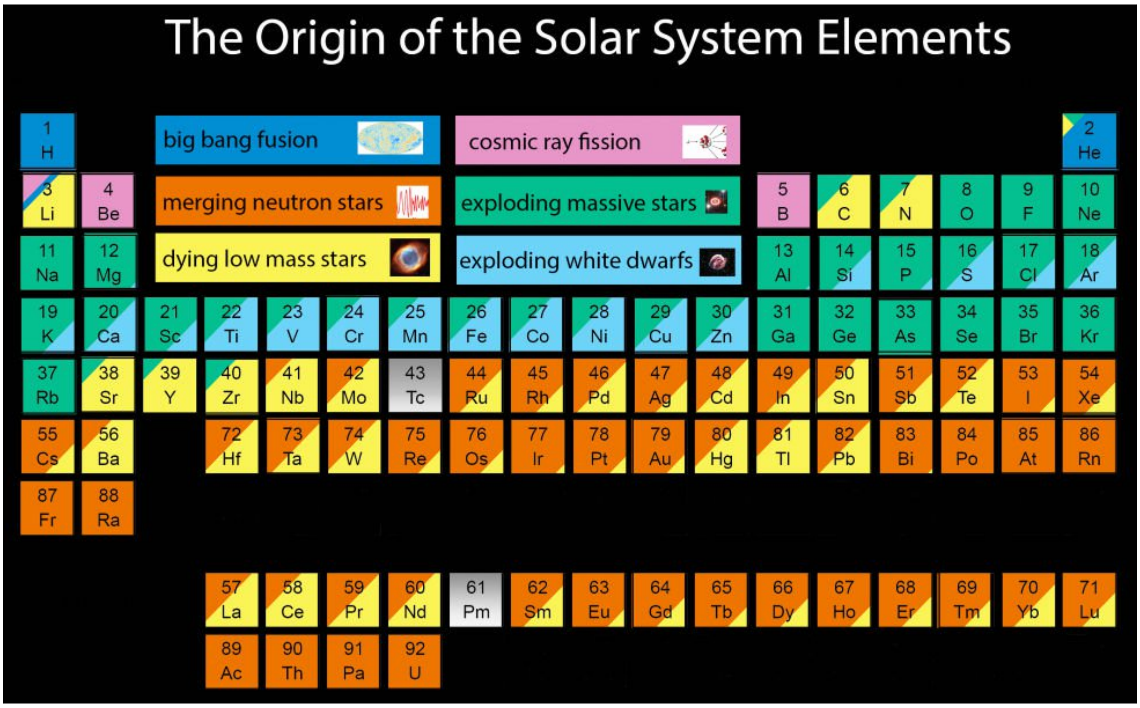

Figure 2: The periodic table of the origin of the elements. The elements originate from a variety of sources, see legend, and the time scale for their productions varies significantly depending of the type of source. Credit: Jennifer Johnson

Several different processes contribute to the enhancement of heavy element abundances in the universe. These include cosmic-ray spallation, normal stellar evolution, supernovae explosions, and compact star mergers. The origin of individual elements is summarized in the periodic table shown in Figure 2. Stars that formed later in the history of the Galaxy, like the Sun, have more elements to build suitable planets. One can see that the elements originate from a variety of sources. The time scales for element production differ significantly. For example, oxygen may be built up early since it originates mainly from short lived high mass stars, while most of the carbon comes from low mass star evolution. Low mass stars are very plentiful, but billions of years are needed for those stars to become dying giants, releasing carbon and nitrogen into the interstellar medium by wind ejection. So, early in the chemical evolution O/C would be large, while late, C/O would be large compared to today. These low mass stars will lock up elements in the form of a white dwarf, which, only if it explodes, supplies a critical element for building Earth-like planets, namely iron. In particular, planets with iron/nickel cores and silicate hydrated mantels can maintain plate tectonics. On Earth, radioactive decay of long-lived species like Th and U have allowed Earth's core to remain hot. These elements require neutron star mergers, likely very rare events. On the other hand, a planet formed out of an excess of Th and U might significantly compromise life. It is clear from Figure 2, that billions of years are required to build up sufficient quantities of life supporting elements. One key to life is the concentration of life's elements, in suitable proportions, in the disks of spiral galaxies. Supernovae in galactic disks are central to this process.

2.1 A Central Role for Supernovae

Supernovae are responsible for the distribution of the elements formed by stars during the stellar lifetime. The supernova rate is related to the rate and process of star formation. High star formation rates likely stress potentially habitable planets due to high energy radiation, particle fluxes, and gamma-ray burst exposure. A Hubble Space Telescope image of the Crab Nebula supernova remnant is shown in Figure 3. Supernovae going off in the disk of the Milky Way forge some of the heaviest nuclei and provide a means for the distribution of the products of stellar evolution. Disk gravity slowly enhances elemental concentration in the disk.

Planets within the disks of spiral galaxies have less exposure to environmental hazards; especially intense particle fluxes and (low metallicity) gamma-ray bursts. Mason and Biermann [2] suggest that the Galactic magnetic disk wind produced by the steady occurrence of supernovae in the disk provides a magnetic protection akin to the heliosphere of the Sun. Galactic cosmic-rays are accelerated by local magnetic fields within supernova remnants [3,4], like the Crab Nebula shown in Figure 3. While the heliosphere stops Galactic cosmic-rays from impacting Earth's atmosphere, the Galactic magnetic field deflects all but the highest energy extragalactic particles. Planetary surfaces not in the thin disk of a spiral galaxy do not benefit from the protection that the Milky Way disk provides Earth. Safe distance from the Galactic center provides additional protection from most Galactic high energy threats.

3. Habitats for Life

The emergence of life awaited the development of habitable environments. Life famously requires energy, water, and nutrients present in sufficient quantities to allow efficient chemical

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Figure 3: The Crab Nebula supernova remnant Credit: NASA/HST

reactions, a key to organic chemistry and metabolism. The existence of a region surrounding a star, usually called the habitable zone, was introduced by Strughold [5], to define a range of distances for which liquid water on an Earth-like planet's surface is possible. The formation of a habitable planet is life's prerequisite. A potentially habitable planet might lose its water, like Mars and Venus, never have water in the first place, or even have too much water. The study of planetary formation environments are critical and the first results are here or on the horizon.

ALMA provided the confirmation, see Figure 4, of the general results from hundreds of years of planetary formation theory. Now we must consider that the planetary environment must survive the effects of its host star(s)' development. Low mass stars, M-types, have prolonged magnetic activity and thus they have habitable zones subject to bursts of XUV radiation and high particle fluxes [6]. On the other hand, stars with only a bit more mass than the Sun have lifetimes that are far shorter. If complex life generally needs billions of years to develop as on Earth, then complex life cannot be supported by main sequence stars that are about 20% more massive that the Sun. Solar type stars and lower mass K-types both have extended lifetimes and activity levels suitable for complex life. Because of the dangers in the central regions of galaxies and low metallicities in

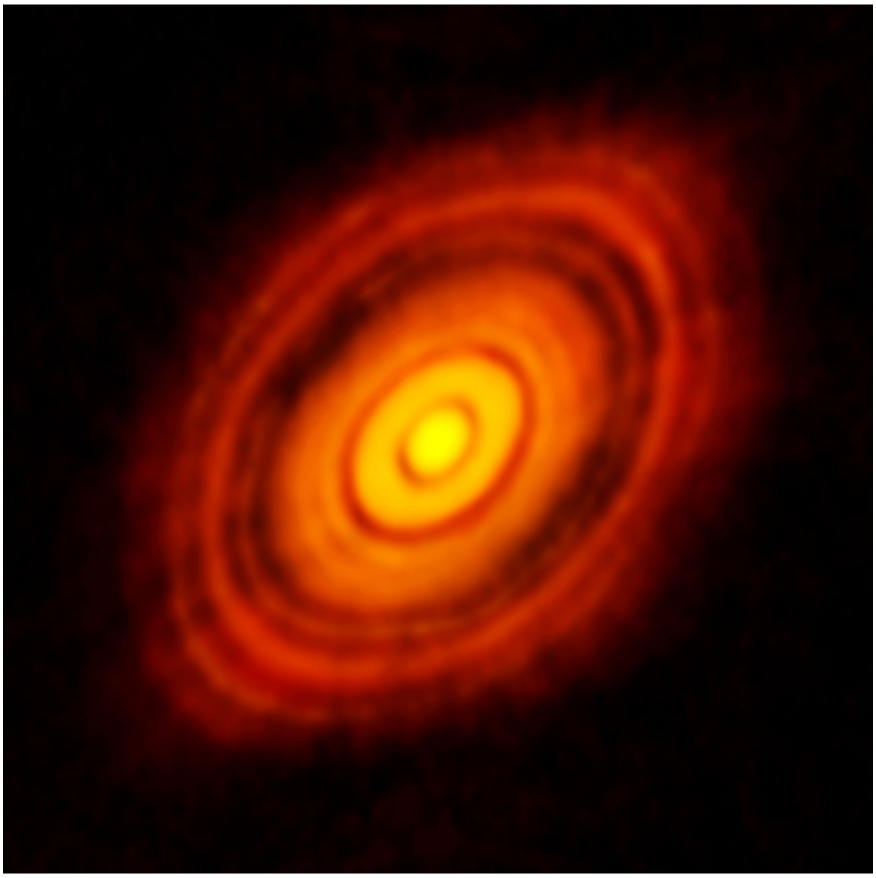

Figure 4: A Planetary System in Formation - HL Tauri. The gaps in the disk are due to planets forming at those distances and their orbital resonances. Credit: ALMA, the Atacama Large Millimeter/submillimeter Array

the outskirts, the galactic habitable zone [6] and super-galactic habitable zone [2] concepts were introduced.

The surface of a habitable zone planet provides the starting point for life to flourish. However, many questions remain open. What makes a planet suitable beyond mere presence in the habitable zone? What could render a habitable planet uninhabitable? This is a question that might be better phrased as: "How much can an otherwise suitable planet withstand before becoming uninhabitable?" What type of star supports the most habitable planets? Within which galaxies is complex life possible? Can life be supported in a binary star system? To this later question: binaries probably host habitable planets. Mason et al. [7,8] suggest that tidal interaction between the stars in a moderately close binary will, in some cases, reduce harmful stellar activity thereby enhancing the habitability of some circumbinary planets. Future grand surveys guided by theory will suggest which stars in the Milky Way are the most likely to harbor complex life or perhaps even a technological civilization of big brains to comprehend it all.

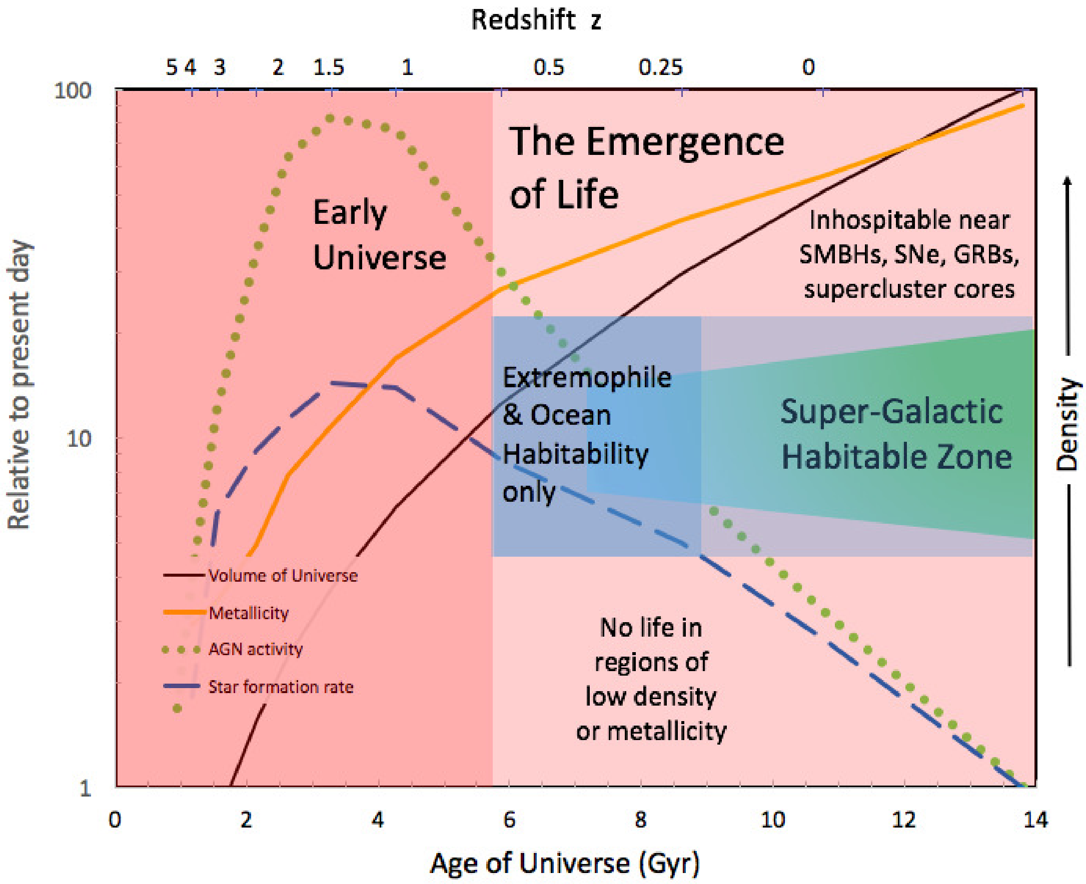

Figure 5: The universe becomes habitable for life in stages. Simple life became possible roughly 9 billion years ago and complex life emerged about 5 billion years ago and then only within the moderate density, Super-Galactic Habitable Zone [2]. Credit: Mason and Biermann (2017)

4. Big Brains Are Not Inevitable

Knowing what circumstances promote or limit the habitability of a planet is only the beginning. We also would like to know, how likely is it that a forming planet will be habitable and once formed how likely is it to remain habitable long enough for complex life to evolve? A wide variety of cataclysms may render a planet uninhabitable. But then consider that the ancestors of every living being on Earth today, includes those that survived many local and global extinctions. Mass extinctions are a double-edged sword. On one side, mass extinctions will compromise life's development by eliminating many species. On the other, niches open up for the survivors and evolution may progress at a rapid pace afterward.

Life then must not only survive many mass extinctions, but it must be molded by catastrophe. What doesn't kill life makes it stronger and more resilient. Predator-prey relationships developed on all scales as kind of a law of mutual evolution. Some of the largest brains in the animal kingdom developed due to this evolutionary force. Brains forged in this manner are highly specialized for particular skills, like agility, or hunting in groups. So, the vast majority of the many lineages of present day species on Earth do not have any need for abstract thinking and novel problem solving, beyond obtaining food and avoiding being food. In other words, the only important thing is passing on copies of their DNA. Big brains, capable of what we think of as rational thought are extraordinarily expensive and are needed only in extreme cases. Humans are extremophiles!

In the case of humans, our brains have tripled in size in the last few million years. This dramatic increase in the ability for rational thought has taken place in just one-thousandth of the time that life has existed on Earth. Dinosaurs evolved many forms and diversified over hundreds of millions of years, but none even remotely developed the intelligence or the means to stop the K-T astroid that ended their reign. The rapid "ascent of man" can be traced to the growth and complexity of the human brain, driven by social interactions [9]. In addition, it can be argued that subsequent advances in tools, agriculture, electronics, and so on, are also driven by social interaction and the need to solve communal and societal problems. The development of tribes, cities, and countries involved the natural selection of big human brains. So, Earth-life tells us that big-brain development can happen quickly under evolutionary pressures, but it is far from inevitable. The vast majority of present day life's successful lineages have not as yet resulted in big brains, within this context, and primates have developed them only recently. For many reasons, life on most exoplanets might not ever reach this threshold. Ultimately, only the development of big brains will protect advanced life from the next avoidable devastation. Predictive science will save species, hopefully here and likely elsewhere, from the inevitable hazards of living in the unforgiving universe.

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