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GREAT MOMENTS IN THE HISTORY OF LIFE

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Introduction

Abstract When looking at events with a geological perspective a "moment" might be a very long period of time. The events discussed here range in absolute time from seconds or days to as long as tens of millions of years. The geologic record is very sparse for extremely old events on Earth, and virtually non-existent for times before the solar system formed. The earliest events, such as the Big Bang origin of the Universe, production of heavy elements in stars, and the formation of the Sun and Solar System can only be understood by general principles of physics, with observation of the current state and activity on astrophysical scales. This early (astro)physical viewpoint shifts to considerations of chemistry and biochemistry even before we arrive at the point where there is a geological record preserved in rocks. Past that point we can describe several important transition points where life turned a corner, and subsequent history of the planet and life entered a new phase. There were bursts of biological innovation and maybe extinction events before we arrived at our current state. What the future holds may well depend on how we apply what we have been able to learn about the past, and how life has responded to changed conditions.

Keywords Astrophysics · Chemistry · Biochemistry · Geology · Extinctions

What might constitute a great moment in Life's long history? What might "moment" mean in this context? It would probably be more accurate to say "turning point" or "transition" but such terms have their own problems. From a geological perspective a moment might be viewed as a rather long period of time, perhaps as much as a million years or more. Our ability to resolve time using what is preserved in rocks is certainly limited. We can sometimes identify very short-term events, such as an enormous volcanic explosion, but this is usually the

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exception rather than the rule. On the other hand, "moment" captures the idea of a significant departure from what previously existed to what follows.

Some of the moments I've chosen are obvious, perhaps even well-known from popular literature, such as the extinction of the dinosaurs. Others may not be so obvious, but are critical in one way or another. The first I discuss, the origin of the Universe, could be taken as a given, except that a closer inspection reveals some very important aspects of this singular occurrence. A lot has been written about the Big Bang, which is now widely thought to be an apt description of an event about 13.5 billion years ago. The details can involve highly complicated discussions of the properties of matter under extreme conditions, but a few are so important in setting the stage for the eventual emergence of life that a brief treatment is, I believe necessary. Closely connected to the origin of the Universe is the development of galactic systems and the development and life cycles of stars. Stars can be looked at as factories engaged in the production (and in some cases dispersal) of chemical elements, including those most vital to living organisms. These first two "moments" (from now on you can assume the presence of the quotes!) are covered together and sequentially in this chapter.

As far as we know we need planets for life to develop. While it is possible to imagine life developing without planets, there are good reasons to focus on the conditions that can occur on planetary surfaces as conducive if not necessary for life to emerge. I use the word "surfaces" quite intentionally. Again, life could conceivably begin in a more or less dense atmosphere such as surrounds the gas giants in our solar system (and probably around other stars, too) but there are reasons to consider terrestrial-type planets with rocky surfaces as a more likely origin-of-life locale. The current search for earth-like planets recognizes the higher probability of life emerging in such a setting. With that in mind, the next moment concerns the processes and resulting conditions attendant upon formation of a rocky (terrestrial-type) planet. These conditions are described in Chap. 2 and set the stage for the next step.

There must certainly be a phase in planetary history, and the ultimate emergence of life, in which prebiotic chemistry assembles organic molecules necessary for life. It is not known, even in the case of Earth, how long this period may have lasted. We still do not know, and may never be able to pin down, just exactly when life first arose on this planet, to say nothing about hypothetical planets elsewhere. Some of the suggestions for earliest life on Earth tend around 4 billion years ago, about 500–600 million years after Earth's formation. It is not unlikely that life could have started much earlier than that, but the absence of preserved material in the geologic record seems to preclude firm conclusions about these earlier times. Still, we can use the very numerous experiments that have been done in laboratory settings to draw some conclusions about what compounds were present and even make some guesses as to where and how (and how probable) life first began. This thinking is clearly informed by what we know of the biochemistry and molecular biology of life. We should, of course, keep in mind that the most primitive life meeting the minimal conditions to be called out as such may be noticeably less complex than what we observe today. Chapter 3 examines these ideas in some detail.

Life presumably emerged somewhere, and quite possibly in more than one place. This latter notion arises because there is obviously some probability of life arising in general, and given the large surface area of the Earth, however low that probability might be for a single instance, it is not out of the question that two or more such moments may have occurred. These could have been close to one another in time or separated in time (and space) by considerable distance. Chapter 4 covers the biogeochemical regimes and processes thought (by me at least) to be most likely to have given rise to life. My conclusions as to the probability of life emerging may be surprising to some. For those of a more technical/mathematical bent I have included a detailed probability analysis in an appendix, but this is not vital to a general appreciation of the issue.

Up to this point we have been dealing with hypothetical events for which little or no concrete evidence has been or can be found. From here we enter times for which there are bits and pieces of evidence in the geologic record that can give us insights into important changes on Earth related to life. The record available is broadly speaking paleontological in nature. It is much skimpier for early times, for which the "paleontology" might be in the form of preserved chemical signatures or geometric traces thought to have been produced by activities of living organisms. As we move closer to the present the preserved record, mostly fossils of the more familiar sort, becomes more obvious. This is especially so starting with the advent of the Paleozoic Era about 550 million years ago. Before we get to this more familiar part of the history of life there are some striking and critical events that happened in the much longer prior Precambrian. The first of these is the development of photosynthesis, the process by which energy in sunlight is captured by organisms to manufacture food molecules for maintenance and reproduction. Chapter 5 discusses the history and types of photosynthesis, and the consequences for Earth and life that result, especially the ultimate production of an atmosphere containing free oxygen.

An oxygen containing atmosphere implies drastic changes in activities, both biological and geological, at Earth's surface. Probably the most important of these for biology was the availability of much more productive metabolic reactions. I suggest in Chap. 6 that this led to viability of larger cells, since movement of nutrients across cell membranes which had previously limited cell size could be overcome by these more powerful metabolic processes. These larger cells could then incorporate smaller cell elements to create the so-called eukaryotic cell, with a separate nucleus and several types of intracellular organelles. This change led to cell types with much expanded capabilities and ultimately to multicellular organisms (Chap. 7).

Following the development of multicellular organisms more sophisticated types of biological organization became possible, including segmented organisms and the development of different cell types in various parts of these multicellular organisms. The expanded capabilities of these more complicated plants and animals, for such they were, opened up "biological space" previously unavailable or marginal for support of life. One aspect of this new space was the ability to move from point to point (animals) or to grow taller from anchors ("roots") in deeper water into sun-lit shallower water (plants). Locomotion was especially important because it allowed non-photosynthetic organisms to move about in search of food. And this led more or less directly to predation, either of plants (grazing) or of other animals (predation in the narrower sense). A consequence of the latter was selection for organisms that had protective features such as tougher outer layers, eventually including hard shells. Not surprisingly this was accompanied or followed by development of more effective tools of predation. These are striking features of the "Cambrian explosion" (Chap. 8) in which the body types of most modern forms developed, but also including some rather bizarre forms no longer represented by living creatures. The development of hard body parts marks the beginning of the Paleozoic Era and the start of a much improved fossil record.

Two striking features of the fossil record are the increase in generic and species diversity over time (though some of this may just be apparent, due to a better preserved record in more recent rocks) and the occasional sudden decreases in diversity which are designated extinction events. These phenomena may be related, and this idea is explored in the next three chapters (Chaps. 9, 10 and 11). Among the moments of interest here are (1) the rise in diversity of fish during the Ordovician through Devonian followed by a major extinction, followed by the (2) colonization of land (Chap. 9). The colonization of land opened an entirely new area of "biospace" and the development of dramatically different (though with clear relationships to predecessors) life forms and styles. These developments were once again interrupted by a major extinction event, which was then also followed by new developments (Chap. 10). The innovations following this Permian extinction gave rise to an array of creatures (dinosaurs) that have fascinated geologists and the public for centuries, and also ultimately led to us, but not until the penultimate mass extinction at the end of the Cretaceous, 65 million years ago (Chap. 11).

The rise of mammals following the extinction of the dinosaurs is, in some ways, the story of the development of neuro-physiological capabilities attending progressively larger and more complex brains. Just how much human beings may or may not differ from the other mammals may be subject to debate, but brain complexity and capacity runs through the middle of any discussion of the last 65 million years right up to the present.

Finally, and because we are in the middle of it (and probably causing it), there is the current extinction event, sometimes called the Holocene (or more recently, Anthropocene) extinction. The reality of this extinction may be debated but, even if it is not on the same scale as those previously mentioned, it clearly has direct meaning for us. And what we can almost certainly say about various aspects of it might even provide a perspective useful in developing policies for addressing our place in the larger ecosystem. Entire books have been written on the subject (also the case for some of the other chapters in this book), so it is dealt with here but briefly as part of Chap. 12.

Suggested Reading

The following readings are of a general nature, covering broad aspects of the origin and history of life. A few cover certain specific aspects in detail greater than that attempted in this small book. Several cover larger philosophical issues. There are additional reading suggestions given at the end of most of the chapters which look more deeply into the chapter topic. In most cases I have tried to find readings accessible to the general reader, but in a few instances I have also included references to more technical works.

The Meaning of Evolution, George Gaylord Simpson, 1967, Yale U. Press.
Life at the Edge, Readings from Scientific American, James L. Gould and Carol Grant Gould, eds., 1989, Freeman & Co.
The Blind Watchmaker, Richard Dawkins, 1987, W.W. Norton Co.
Life: A Natural History of the First Four Billion Years of Life on Earth, Richard Fortey, 1999, Vintage.
The Dragons of Eden, Carl Sagan, 1977, Random House.
Major Events in the History of Life, J. William Schopf, ed., 1992, Jones and Bartlett.
Life Evolving, Christian de Duve, 2002, Oxford.
Life Ascending, Nick Lane, 2009, Norton.

2

In the beginning….and somewhat later

Abstract The Big Bang, which initiated the Universe more than 13.5 billion years ago, produced all the matter there is. It was almost entirely hydrogen and helium, with a tiny fraction of lithium and beryllium. There was no carbon, nitrogen or oxygen at first. Nuclear fusion, the power source of stars, resulted first in the production of more helium, but this was followed by further fusion to produce the more massive elements up to iron. Enormous explosions of dying massive stars produced even heavier elements, and importantly, blasted a complete array of heavy elements into space, where the next generation of stars was formed, but this time surrounded by clouds of solid particles, the raw material from which planets formed.

Keywords Big Bang · Fusion · Supernova · Heavy elements

In some ways it is trivial to say that having a universe is a requirement for having life. Leaving aside the philosophical convolutions of what it might mean to have life without a universe, our knowledge of the conditions attending the formation of the universe, assuming the Big Bang model is correct, is actually very informative. The Big Bang model is the result of observations and theoretical considerations going back nearly a century to when Edwin Hubble made the first systematic investigation of the motions of galaxies, especially their motions away from Earth. The consistency of the relationship between red-shift and distance is striking. Red shift, measured using spectroscopic measurements of light emitted by stars or galaxies, has a very direct relationship to the speed at which objects are moving away from the observed. In the case of galaxies, more distant galaxies are moving away (have a larger red-shift) than galaxies that are closer. The conclusion Hubble drew was that the universe was expanding, presumably from an initial much more

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compact state. Assuming everything could be brought back to the starting point immediately suggests an origin as a cosmic explosion from an incredibly dense beginning. This leaves open the question of how such an event may have happened, including the question of what may have preceded the event. Such speculations may be interesting but here we are more concerned with conditions in the very early stages of the Big Bang itself. Indeed, this is probably the closest thing to a moment that we will consider in this book.

Cosmologists have given a lot of thought to the conditions immediately following the Big Bang, "immediately" meaning the first tiny fractions of a second to several minutes. A simplified version is shown in Figure 2.1.

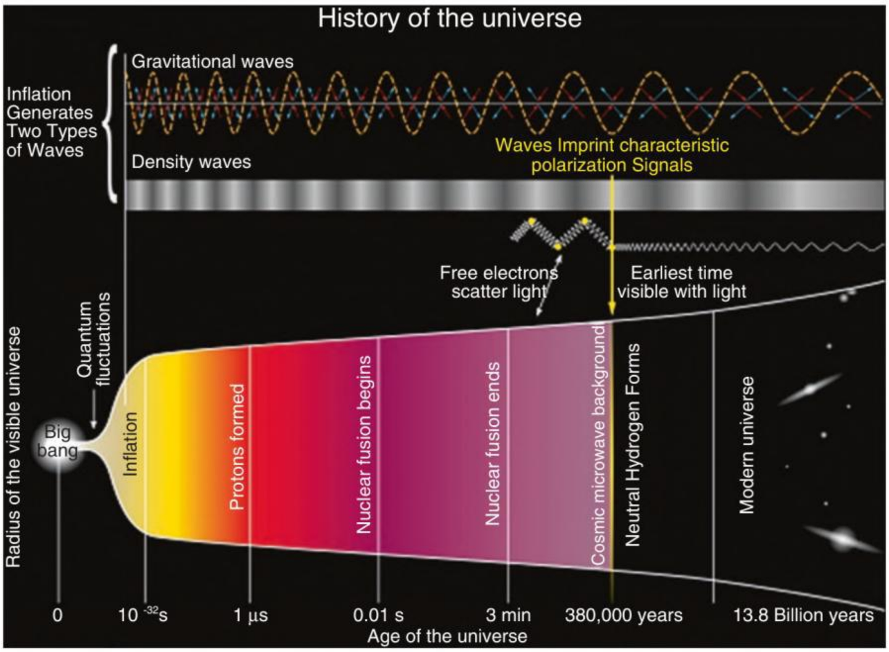

Figure 2.1 Early history of the universe. By Original: DrbogdanVector: Yinweichen – Ownwork,CCBY-SA3.0,https://commons.wikimedia.org/w/index.php?curid=31825049

During this incredibly brief period of time all of the matter we can now observe, and a good fraction of the electromagnetic energy, was produced by high energy processes in a dense, but rapidly expanding blob. Of most interest to us here is this formation of protons, neutrons and electrons that make up the stuff of living things. Within the first 3 seconds or so all of these bits of matter were created and some of the protons and neutrons even clumped together to form helium nuclei *image not available*

The additional heating results in the production of yet more energy through fusion of hydrogen in the layer surrounding the core of the star, which causes expansion of the outer layers In other words the star gets larger. The size increases enough to allow the star to lose the extra energy at a lower surface temperature, so the star becomes redder (a characteristic of lower temperature as mentioned above). Stars smaller than the sun, and going up to about 1–1/2 times the mass of the sun, all basically do the same thing, although the larger stars progress more rapidly because they use their extra fuel disproportionately fast. All of these stars have a relatively quiet life cycle and don't manufacture especially heavy elements through fusion. It is the larger stars, and especially those starting with masses eight or more times the mass of the sun that are the important nuclear factories producing (and dispersing) the elements necessary for life.

These more massive stars run through their hydrogen fuel very rapidly. A star about 10× the mass of the sun runs out of hydrogen in its core after about ten million years, and more massive stars have even shorter hydrogen fusing phases. When the hydrogen runs out they then fuse helium to heavier elements like carbon and oxygen, but the energy released is much less for each atom of helium undergoing fusion. This means that the helium fusing phase lasts for a much shorter period of time than the hydrogen fusing phase. Figure 2.3 is the "curve of binding energy" that shows how much energy is obtained for each nucleon (neutron or proton) during fusion of the various elements, starting at hydrogen and progressively moving to heavier and heavier nuclei undergoing fusion toward the right.

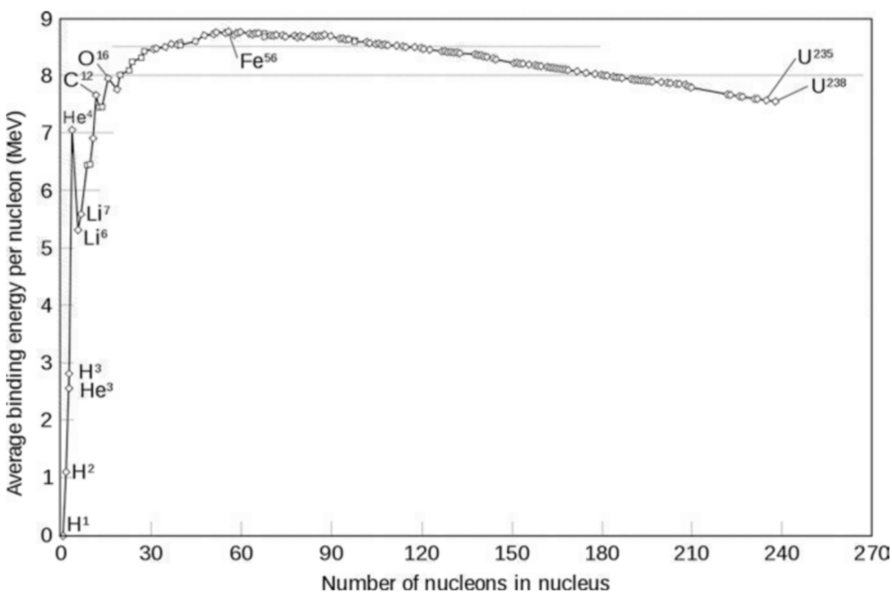

Figure 2.3 The curve of binding energy, showing the energy available (or needed) from/for nuclear fusion (Fastfission, wikimedia commons)

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