THEORETICAL MODEL FOR OTHER CIVILIZATIONS IN THE GALAXY AND THE LIKELY ISOLATION OF HOMO SAPIENS

by

Anirban DasGupta
Purdue University
and
University of Pennsylvania

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Department of Statistics
Purdue University
West Lafayette, IN USA

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Dedicated to Larry Brown

I shot an arrow into the air,
It fell to earth, I knew not where;
For, so swiftly it flew, the sight
Could not follow it in its flight.

I breathed a song into the air,
It fell to earth, I knew not where;
For who has sight so keen and strong,
That it can follow the flight of song ?

Long, long afterward, in an oak
I found the arrow still unbroke;
And the song, from beginning to end,
I found again in the heart of a friend.

Henry Wadsworth Longfellow

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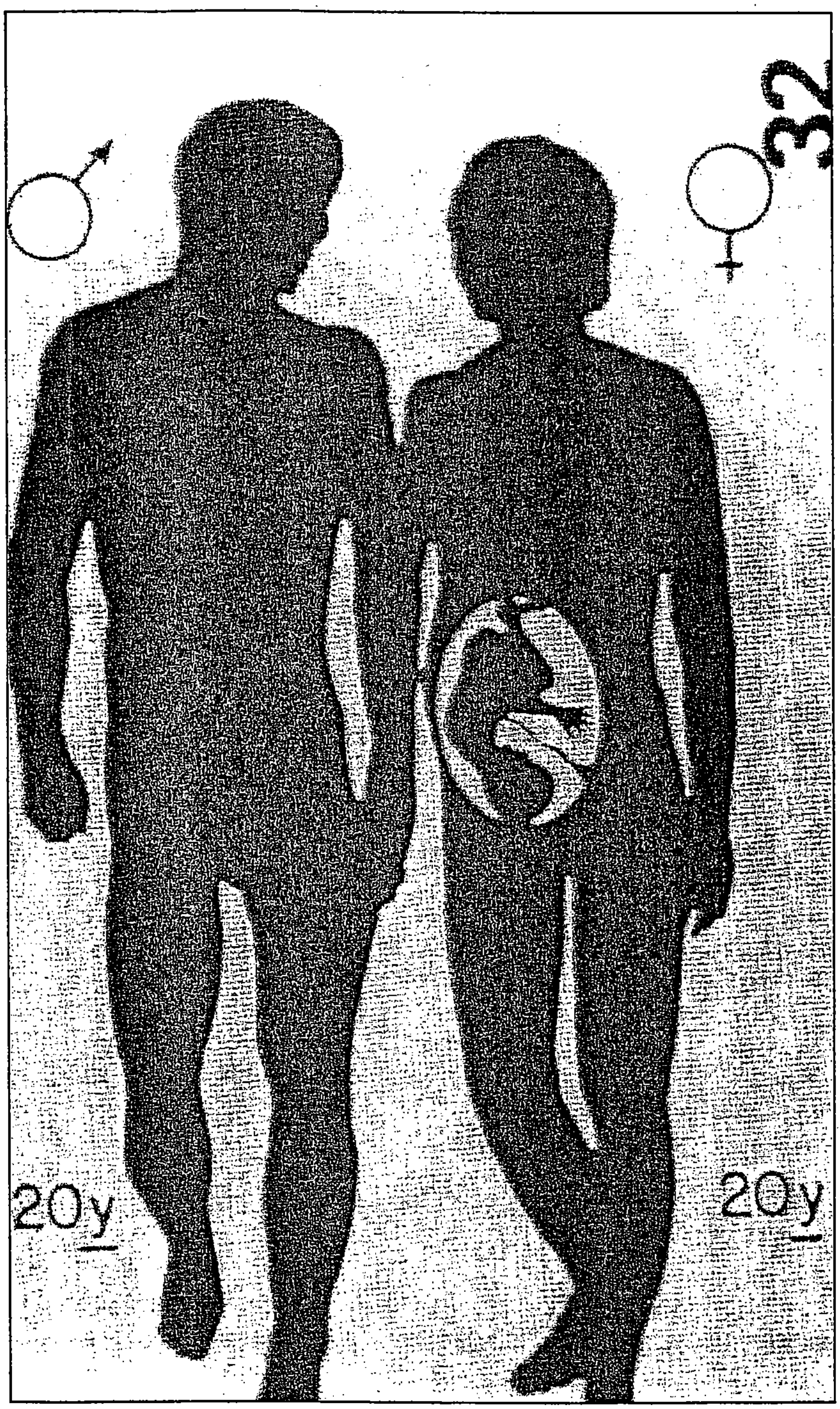

Figure 1. An image from the record sent along with the Voyager spacecraft, now on its way into interstellar space. *(Photo: Courtesy The Astronomical Society of the Pacific.)*

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anirban@wharton.upenn.edu

Abstract

The question if Homo Sapiens is alone in the universe has been asked by philosophers, scientists and citizens for many thousands of years. The question lies at the edge of the limits of science. Not only is it about the most difficult question that one can ask, if we came to know the answer to this question, it would be the ultimate knowledge for Homo Sapiens. The question is so difficult to answer because it lies at the intersection of almost all the sciences: physics, biology, astronomy, chemistry, geology, and of course mathematics.

Section 2 gives a mostly nontechnical introduction into what are the relevant factors that would determine the answer to the question. Section 3 gives a theoretical probabilistic model, using the universally accepted Drake equation as the paradigm. Section 4 states the technical results that follow from the theoretical model. Section 5 gives a detailed simulation of the theoretical model. Section 6 extends the results of the simulation to find estimates for the distance to the nearest advanced civilization. Section 7 reports a sensitivity analysis on the theoretical model. Section 8 is a technical appendix that gives the derivations of the results of Section 4.

The simulations lead to the estimate that if any advanced civilizations at all exist, then the distance to the nearest one is 25,500 light years. This was extracted from the simulations by also assuming a compound spatial Poisson process for the distribution of civilizations. This figure, and the sensitivity analysis would suggest that there is almost no hope that Homo Sapiens would be able to either detect or contact companions in this

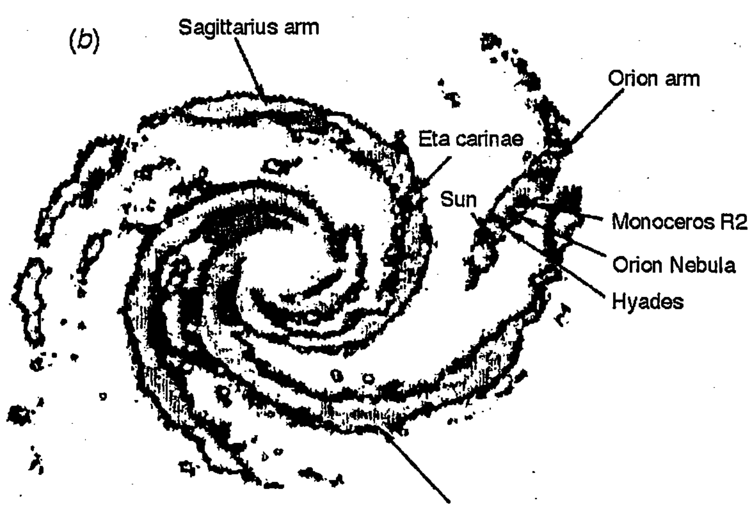
seemingly endless universe. And many have said that was precisely the "mind of God".

1. INTRODUCTION

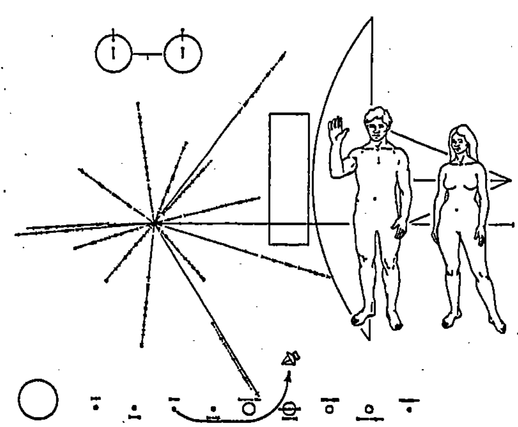
The Hubble space telescope reveals as many as 3 million galaxies per square degree in the sky. The entire sky covers about 41,000 square degrees. Thus a crude, but apparently extremely conservative, estimate is that the observable universe has about 125 billion galaxies. Homo Sapiens, that is us, came into being roughly 100,000 years ago, on Earth, the third planet in orbit around the sun, one star in the spiral Milky way galaxy of up to 400 billion stars. By virtue of our own existence, we have proof that consciousness and "intelligence" have developed in the universe. Nobel Laureate Jacques Monod (1910-1966) says, in his renowned monograph "Chance and Necessity", "Man knows at last that he is alone in this unfeeling immensity of the universe, out of which he has emerged only by chance ...The universe was not pregnant with life, nor the biosphere with man. Our numbers came up in the Monte Carlo game." Indeed, one of the ultimate questions of humanity is whether we are alone. The question is not new; to paraphrase Steven J. Dick (1998), one may ascribe it to "deep psychological yearnings for companionship and superior wisdom", and if we ever possess the answer to this ultimate question, that would be the ultimate knowledge. For then, we will truly learn the place of humanity in the universe, and to many, it will finally unravel "the mind of God". Many opine that the question is at the very edge of the limits of science, and indeed lies squarely at the intersection of astronomy, biology, physics, chemistry, philosophy, mathematics and religion.

I do not believe that the question, as momentous as it is, is merely of philosophical value. Homo Sapiens has selfish reasons to address the question. If we were to discover that advanced civilizations can last for substantial periods of time without getting destroyed, by some built-in mechanism, that will be useful and comforting knowledge. The SETI (Search For Extraterrestrial Intelligence) movement with the active participation of eminent scientists and NASA is ample proof that there is scientific interest in the question. The question is far from being frivolous. I will keep the article focused on the scientific and technical aspects of the question. Thus, there would be no discussions of UFO sightings, alleged alien abductions, the Gaia hypothesis, or other sensational claims without credible proofs.

As is well recognized, sentiments run deep and strong on the likely answer to this question. Biologists tend to believe that the creation of life itself was an event of extraordinarily low odds; astronomers, on the other hand, discard the notion of a fluke, even if we do not know the process of origin of life, and think that processes similar to what happened on Earth would transpire elsewhere under the right environment, and would give rise to possibly other forms of life. The conflicting opinions are clear from the following statements by Ernst Mayr and Paul Davies. Ernst Mayer says: "A full realization of the near impossibility of an origin of life brings home the point how improbable it was. The chances that this improbable phenomenon could have occured several times is exceedingly small, no matter how many millions of planets in the universe." Theoretical physicist Paul Davies, on the other hand, says: " So I say, no miracles and no stupendously unlikely accidents. . . .Life and consciousness, I believe, are typical products of physical complexity, a product of law, and not chance alone. To be sure, many of the features, both physical and mental, of our make-up certainly are a product of chance, but the general emergence of consciousness is something that is assured."



Milky Way galaxy, showing three nearby arms, and the positions of regions of new star formation and of the Sun.



The plaque on the side of the *Pioneer 10* and *11* spacecraft depicts a man and a woman and other information designed to illustrate from where and when in the galaxy the spacecraft was launched.

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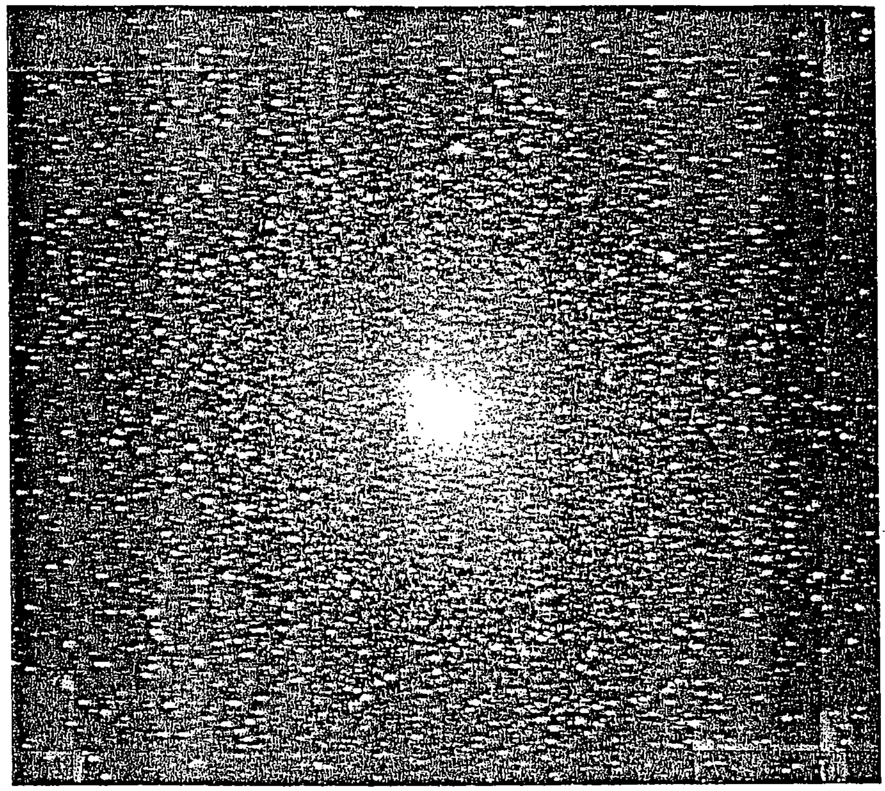
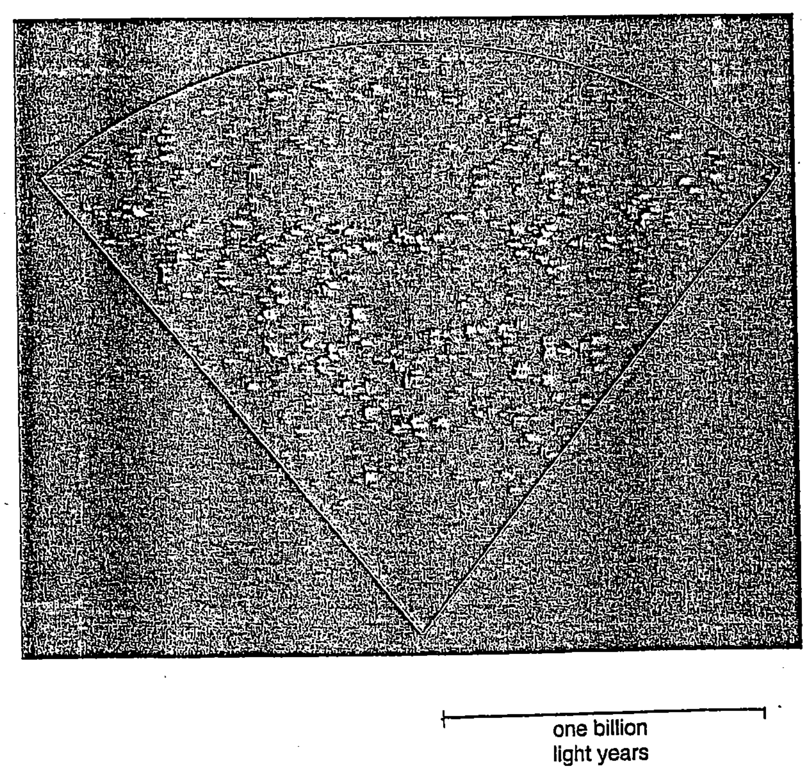
Even if opinions differ dramatically, the path to origin of consciousness and intelligence is more or less agreed on. Astronomer Frank Drake summarized the pathway succintly into what is now universally known as The Drake Equation. In its original form, the Drake equation says that the number N of advanced civilizations in the galaxy (Milky Way) is given by

$$N = R * \theta_p * n_e * f_l * f_i * f_a * L \tag{1}$$

where R is the star formation rate in the galaxy, θ_p is the fraction of stars having a planetary system, n_e is the number of habitable planets per planetary system, f_l is the probability of life developing in a habitable planet, f_i is the probability that life, once it arises, advances to intelligence, f_a is the probability that intelligence advances to advanced civilization, and L is the lifetime of such a civilization. Effectively, the Drake equation puts together the steps necessary in the development of a civilization, using our Earth as a model. As one may surmise, the state of knowledge about the quantities involved in the Drake equation is partial or simply blank. Thus, it is not surprising that if one naively substitutes personal fixed values for these quantities into the Drake equation, one gets a hopelessly large range of answers for N, the number of civilizations currently existing in the galaxy.

Perhaps it would be useful to briefly describe now what I have done here. I have done what an applied mathematician does. I have taken the universally accepted paradigm of the Drake equation, and have adjusted it according to current trend. For example, the model has been adjusted to accommodate mass extinction events. I have written a (fairly complex) probabilistic model for the individual quantities in this revised Drake equation, instead of substituting subjective single values for them. I have used available data, as much as I could, in writing the probabilistic model. When I found little or no reliable information, my model reflects that lack of information, typically by using a probability distribution with high uncertainty. The model was then analyzed, analytically, and then by a simulation. I use the results of the simulation to make predictions and answer some questions that seem to be of obvious interest. For example, in 52.4% of the simulations of the model, no advanced civilizations exist at the present time in the Milky way galaxy; the average number is 6.88 over all the simulations. And IF any advanced civilizations do exist at the present time, the simulations give the result that the distance to the nearest one is just over 25,500 light years. This would formally validate the RARE EARTH hypothesis, *The globular star cluster 47 Tucanae, at a distance of about 4 kiloparsecs. Clusters such as this contain the oldest stars in our Milky Way galaxy; and are used to establish a minimum age for the universe, if we allow one billion years for the cluster to form, of about 15 billion years.*





Galaxies are not distributed uniformly in the universe but occur in clumps and strings. This shows the lumpy distribution of galaxies out to about two billion light years, based on a survey of 24000 galaxies (Carnegie Institution Las Campanas Survey).

recently proposed by Peter Ward and Donald Brownlee (2000). If one is to take the prediction from this simulation on its face value, then there is almost no hope that we would ever be able to detect or meet another civilization.

I should mention here that the probability distributions I have chosen for a number of quantities in the Drake equation would be regarded as extremely optimistic by biologists and evolutionists. In other words, the pessimistic estimate that the civilization nearest to Earth is 25,500 light years away is to a large extent the output of an optimistic model. Why such a pessimistic answer from a generally optimistic model? The calculations later will show that a principal reason is that the quantity L, the longevity of advanced civilizations, CRUCIALLY affects the final outcome of the simulations. We know almost nothing about L. My selection of a probability distribution for L reflects this almost complete lack of knowledge. As a result, in the simulations, it was not uncommon for civilizations to arise and get extinct before they could arrive at the present epoch. On the other hand, the simulations also resulted in some civilizations that survived for astonishingly large time periods, over 25 million years, and but for these, the average value for N in the simulations would have been even smaller than 6.88, the value we obtained.

Complicated as the question is, I will describe the context for the construction of the model leisurely. Most of this would be common knowledge to specialized experts in the area, but not so, I suspect, to the broader audience I have in mind. The mathematics is unavoidable. To retain the flow of the main development, divorced from the mathematics, I have deferred almost all the technical calculations to the appendix. Undoubtedly, there would (and should) be disagreements about details of the probabilistic parts of the model. I do hope that others will run models that are similar in spirit but different in the details, and simulate these models. It would be useful and interesting to compare the results of these different simulated models.

2. SOME HISTORY, PHILOSOPHY AND SCIENCE OF THE DEBATE

2.1. HISTORY AND PHILOSOPHY

The idea that living beings inhabit "other worlds" besides Earth has existed since at least the 3rd century B.C. The debate centered more or less exclusively around philosophical issues, until about the middle of the nineteenth century when French mathematician Pierre-Simon de Laplace first suggested that the solar system arose out of a long and complicated process as opposed to being created instantly by the intervention of a creator.

The view that somehow Earth is unique and there can never be anything resembling humans elsewhere in the universe was shared by a number of early eminent philosophers, Plato and his student Aristotle among them. Given that the consensus of the time, all the way till Copernicus, was that Earth was the center of the universe, it does not seem surprising that uniqueness of humans was also the prevailing view.

The competing view that a plurality of inhabited worlds exist was expressed by the so called atomists. Notable among the believers in pluralism were Democritus, Epicurus, and the Roman poet Lucretius. Lucretius, in De rerum natura, argues that a plurality of living worlds must exist "since there is an unlimited space in every direction, ... and when abundant matter is ready, when space is at hand, and no thing and no cause hinders, things must assuredly be done and completed."

The Copernican revolution was a defining moment. By first placing the sun at the center of the solar system and the planets going around the sun, Copernicus made a seminal contribution to the subsequent development of cosmology and if unintended, stripped Earth of the dogma that it was meant to have a central or a special role. But Copernicus, himself, did not address the pluralism issue. Kepler, a devout Copernicun, seems to be the first scientist to have explicitly suggested the existence of extraterrestrial life. Kepler went as far as suggesting inhabitants in Earth's moon, and said: "Our moon exists for us on the Earth. Those four little moons (discovered by Galileo) exist for Jupiter, not for us. Each planet, together with its occupants, is served by its own satellites. From this reasoning we can deduce with the highest degree of probability that Jupiter is inhabited."

Interestingly, Galileo, and later Newton and even Descartes did not fully entertain the idea of other inhabited worlds. Newton, ambivalent about the existence of other living worlds, quite firmly held the view that "the formation of ALL ordered systems was contingent on God's will." But the great German philosopher Immanuel Kant made an influential contribution to the extraterrestrial life debate. Some of the theories put forward by Kant seem hilarious today. For example, Kant suggested a sequentially more intelligent chain of inhabitants further out from the center of any (solar) system. Thus, the inhabitants in Saturn, according to Kant, would be far superior than those in Mercury and Venus. The most consequential contribution of Kant was probably his unapologetic pluralistic stand.

While major scientific advances were being made, the debate continued to linger on reconciling the plurality of worlds with christianity and the will and omnipotence of God. If in fact there were a multiplicity of worlds, all inhabited, why or how would God engage in masterminding and maintaining them all? To the question of purpose, namely that it would be manifestly pointless for the creator to create a seemingly endless universe with only one inhabited planet, William Whewell responds: "... geology reveals human existence on Earth to be but a short atom of time compared to the age of the Earth; therefore, why could not intelligence be confined to the atom of space, that was Earth?" Pluralists, on the other hand, denied God any (significant) role in the continuous masterminding of the universe, and argued that a multiplicity of worlds, all with their own lives, was more consistent with the power and the omnipotence of God. The reconciliation between the christian belief that God created man in His own image and the plurality of worlds was, alas, never really achieved. But with the advent of science, the new observations, and the evolution of cosmology as an established scientific discipline, the extraterrestrial debate appeared to focus on the scientific issues, to which we now turn.

2.2. UNDERSTANDING THE FACTORS IN THE DRAKE EQUATION

The scientific argument against life or advanced life in other planets seems to primarily rest on a sequence of events in the history of Earth that have an appearance of being incredible accidents or coincidences. The argument generally put forward is that Homo Sapiens would not have arisen but for this sequence of near miraculous accidents, and it stretches logic and imagination that these requirements would have been met elsewhere in the galaxy, or for that matter the entire universe. To an objective and unbiased eye, the coincidences do not automatically preclude development of extraterrestrial advanced life; after all, as Carl Sagan pointed out, "the precise sequence of events that have taken place here have probably not occured anywhere else. But there should be many functionally equivalent pathways to a similar end result." (Dragons Of Eden, 1977). However, from an educational point of view, it is very interesting to discuss these so called coincidences, and in fact, a discussion of these events, I think, is absolutely essential in constructing a plausible probabilistic model for the factors in the Drake equation. Let us discuss a number of these so called lucky coincidences.

2.2.1. THE LUCKY NATURE OF OUR SUN

The basic premise is that for Earth-type life (carbon based) to arise, sustain, and evolve through a long (Darwinian type) evolution, the parent star would have to be pretty special, in a number of ways, and so it looks like a lucky accident that our sun has all of these properties that are pretty special.

First, the principal properties of our sun. Although this is widely available, the details tend to be a bit different depending on where one looks. The information given below is from the fourth edition of Allen's Astrophysical Quantities (2000, edited by Arthur N. Cox), Ward and Brownlee (2000), Darling (2000), Heidmann (1997), Jakosky (1998), and Odenwald (1998).

Sun is a yellow main sequence star of spectral type G, about 9 kiloparsecs (i.e., about 30000 light years) distant from the center of the Milky way galaxy. We will discuss the age of the sun in greater detail in section 3 during the presentation of our probabilistic model, but right now let us just say that its age is estimated to be somewhere in the range of 4.5 to 4.7 billion years. The significance of the letter G in the spectral type is that neutral metals dominate the spectrum of sun. The surface temperature of sun is about 5700 degrees (centigrade). Being a main sequence G star, its total lifetime is of the order of 10 billion years. So our sun has a residual life of about 5.5 billion years. The lifetime can be calculated from the rate at which the star is fusing hydrogen into helium, and it is rather remarkable that 80 years ago Arthur Eddington was able to calculate the sun's lifetime at the presently accepted accuracy level. The sun is not sufficiently big to undergo a nova. Once it leaves the main sequence, that is the current stable period, it will become a so called red giant. Nobel Laureate S. Chandrasekhar proved that a red giant would collapse if its mass exceeds 1.44 solar masses. Since obviously that is not the case with the sun, it will become a white dwarf. We shall discuss the dying sun and the associated fate of the planets later in section 3 as part of the construction of our probability model; let us simply note here that Earth will be cannibalized by the sun long before its final transformation into a white dwarf. We need to note another fact about the sun here. Although we have no visual proof, but infrared observations show that the Milky way galaxy is a (barred) spiral galaxy with three distinct arms, the Sagittarius, the Orion, and the Perseus arm. The sun resides in the gas and dust rich Orion arm, and completes one revolution around the galactic center in approximately 200 million years. One notable coincidence: the stars generally take longer to complete one revolution around the galactic center than do the arms, as a whole. But the Orion arm also takes approximately 200 million years to complete one revolution around the galactic center. It is claimed, for reasons I shall mention below, that this lucky coincidence is a consequential factor in a long evolution of life having been possible in a planet around the sun.

We can now discuss why the sun is considered a special star, as far as the existence and evolution of life is concerned. First, life as we know it, requires the availability of metals and heavy elements. Metals and heavy elements were not available initially in the universe and became available as remnants of supernovae of the first generation stars. Thus, a parent star having a planet harboring life that requires metals, has to be, like our sun, a second (or later) generation star. Second, up to 50% of the stars in the galaxy are binary stars; that is, they form a system of two (actually more, sometimes) stars bound together by a shared gravitation and orbiting around a common barycenter. It is generally believed that a habitable planet in a stable orbit could not form around binary stars. Although opinion is not unanimous, it seems that most astronomers think that the gravitational disturbance due to each star would cause the planet to have an erratic orbit, resulting in the planet's ejection into space or collision with another planet or star. I should mention here that astronomers do not take seriously the sometimes mentioned hypothesis that sun itself has a dwarf companion, fictionally known as the Nemesis star.

Next, essentially all the material properties of a star are dictated by its mass. The masses of stars have a pretty wide range, from about one-fifth to about 30 times the solar mass. The supergiants with a huge mass burn off their fuel way too fast, and leave no room for origin of planets or life. These stars have spectral type O, A, or B. On the other hand, small stars that burn their energy in a frugal manner, such as the stars with spectral class M, have very weak radiation, and the ecosphere around them, that is the spherical shell in which a planet could arise and be at all habitable, is extremely small. Furthermore, a planet around such stars would always face the same way with respect to the star, and therefore the other side will be permanently frozen, and the bright side will (likely) be constantly too hot. For example, any life above the level of eukaryotic microbes could not survive at temperatures above about 125 degrees fahrenheit. Consequently, for metal-based life to exist, the parent star, it is generally agreed, has to be a second generation star with spectral class G or K; in the Milky way galaxy, the estimated percentage of G or K stars is about 20%. If we tentatively assume (although we will do a more detailed calculation in section 3) that there are 200 billion stars in the galaxy, then that gives about 40 billion stars that are at all admissible. This is still a very large number, but I will now describe why it is believed that the actual number of possible candidates is much smaller.

It has something to do with the revolution period we discussed before. Because the sun revolves around the galactic center at coincidentally the same speed as the arm, it is able to avoid cutting into the orbit of a spiral arm all too often, which would have happened if the arm was revolving much faster (that is, it will come from behind, so to speak, and cross the sun, frequently). The spiral arms are poisoned with old supernovae, and as the star crosses a spiral arm, the absolutely lethal radiation is likely to sterilize most life. Evolution, as it happened on Earth, took about 4 billion years. It is interesting to note that the last time our sun crossed a spiral arm was about 4.5 billion years ago, and the next crossing is several billion years away. To paraphrase astrophysicist Fred Hoyle (of the steady-state theory fame), it looks like someone "was monkeying with the laws of physics" and it looks as if it was a "put-up job."

Apparently, the computations show that for a star to avoid crossing into the orbit of a spiral arm to allow enough time for an Earth-like evolution to occur, the star needs to be at a distance of about 30,000 light years from the galactic center, just as the sun is, and needs to be in a very narrow ring that is estimated to have only up to 1 billion stars, a number considerably smaller than the 40 billion we derived before.

So it seems that the sun has all the right properties needed of it to have a habitable planet on which life could evolve over a very long period of time. As a result, some call it a lucky star.

2.2.2. CONSTRUCTING PLANETS: EASY OR DIFFICULT

Although it has been mentioned by many prominent astronomers that life, either primitive or very exotic, can exist outside of the environs of a planet, here we talk only about Earth-like life on a planet. Afortiori, it becomes important to discuss the formation of planets. The truth is that although there appears to be a movement towards the so called accretion theory, there is still significant uncertainty about the formation and abundance of planets. It seems that the question of abundance of stars having planets will have to be eventually decided by observation, a topic that I will discuss shortly. I should also mention here that a sizeable body of planetary scientists seem to hold the view that there is no single universally applicable method of formation of planets, and planets probably form in all sorts of ways under different circumstances. Here I will only describe the presently common accretion theory.

It is interesting that after nearly one century of alternative theories on the formation of a solar system, the one proposed by Laplace in 1796 is now beginning to take hold in the larger astronomical community. Laplace had suggested that the sun and the planets formed from a rotating disk of gas and dust that had broken off from a huge molecular cloud; Laplace called this disk the SOLAR NEBULA.

The theory is that a nebula breaks off a gigantic cloud due to a number of possible reasons, such as shock waves from supernovae or under its own gravity. It then starts to spin rapidly; indeed, it spins so rapidly that it separates into a central accumulation, one that would become the star once the nuclear fusion begins, and a surrounding disk, called the protoplanetary disk. Planets will ultimately form out of this protoplanetary disk.

Here is what the accretion model suggests. The protoplanetary disk had a lot of localized turbulence, and the grains in the disk started to collide with each other. Collision caused growth by sticking together to occur, and once the grains grew to the size of planetesimals, they started to gravitationally attract each other. This had the snowball effect of increasing the rate of collisions, causing further growth in the size of the planetesimals.

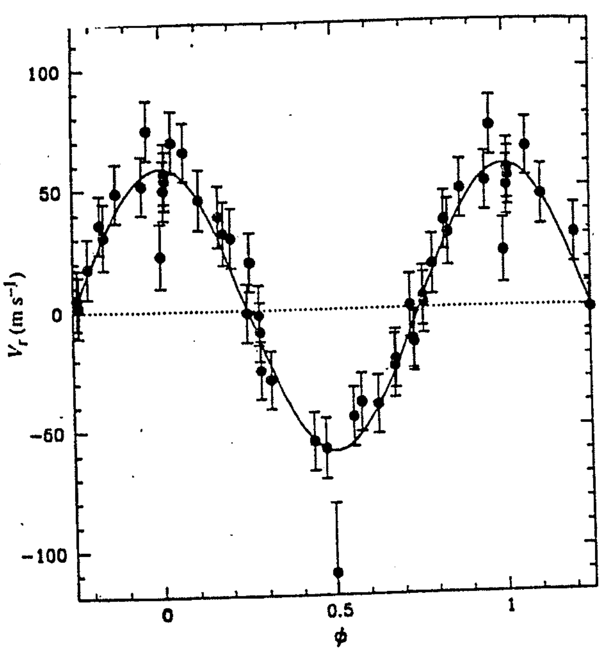
In the meantime, the nuclear furnace of the star has already ignited, and so the area nearer the star is hotter. The heat and the strong solar winds drive the gas away from the regions close to the star. The theory is that the accretion process further out results in planetesimals far larger in size, and because they are so much larger in size, they have enough gravitational pull to now capture the gas as well. This results in a couple of gas giants with still a rocky core, like Jupiter and Saturn in our system.

As regards the planetesimals closer to the star, they will not have any significant amount of gas as the gas has been driven away. They will continue to collide with each other, and one, like Earth, grows comparatively larger than the others. The remaining planetesimals are now adequately big that they start to cause eccentric confusion in each other's orbits, and a large number get ejected out of the system. The ones that remain form a few other smaller rocky planets, like our Mercury, Venus, and Mars. And some ice giants, like Uranus and Neptune, form very far out because they do not get a chance to trap any gas after the gas giants have formed. There is a theory for formation of something like an asteroidal belt adjacent to the first gas giant as well, but it is not quite central to the article.

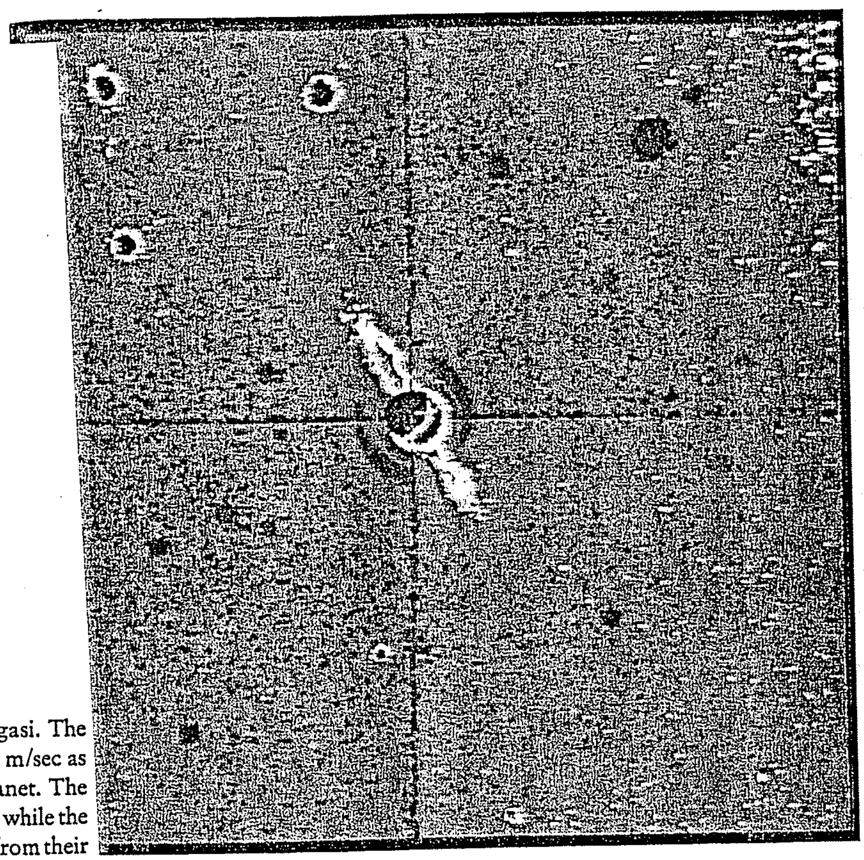
This is the currently accepted theory. What does the theory say about the ease of constructing planets? Simulations reported in Wetherill (1991, 1996), and Jakosky (1998) indicate that Earth-like planets formed, relatively easily, at 1 to 3 times the distance of the distance of our Earth from the sun (i.e., 1 AU). What about the actual observations based on planetary searches? What do they say? That is what we discuss next.

2.2.3. EXTRASOLAR PLANETS: DISCOVERY AND STATUS

Although direct imaging may be possible in the near future, planets and other stellar companions are currently detected by three principal indirect means. As a companion moves around a star, the two bodies exert gravitational influence on each other, and as a result such a companion would produce a gravitational perturbation in the motion of the star. By carefully measuring this reflex wobbling motion, the presence of a companion can be inferred; this is the astrometric method. A second method, known as the photometric method, detects a companion by observing the diminution in the light from the star, as the companion passes right in front of it. The third method, called the spectroscopy method, studies the shift in the spectrum of a star due to the change in its radial velocity brought upon by the tugging of the companion one way to the other as it orbited around the star. Planets around pulsars may be inferred by an alteration of the pulsar's otherwise clocklike pulses. In addition, the Hubble space telescope has detected protoplanetary disks around a number of stars, some very very young, an encouraging development that we will discuss below.



Evidence of a planet with about one-half Jupiter's mass around 51 Pegasi. The .usoid represents a line-of-sight variation in the motion of the star of ±59 m/sec as : star is tugged one way and then another over 4.2 days by the inferred planet. The ectroscopic "Doppler" method works best for planets close to a parent star, while the rometric method depicted in Figure 3.5 is optimal for planets more distant from their .r. Reprinted with permission from Michel Mayor and Didier Queloz, "A Jupiter-ass Companion to a Solar-Type Star," *Nature*, 378 (1995), 355–359, copyright 1995 Macmillan Magazines Limited.



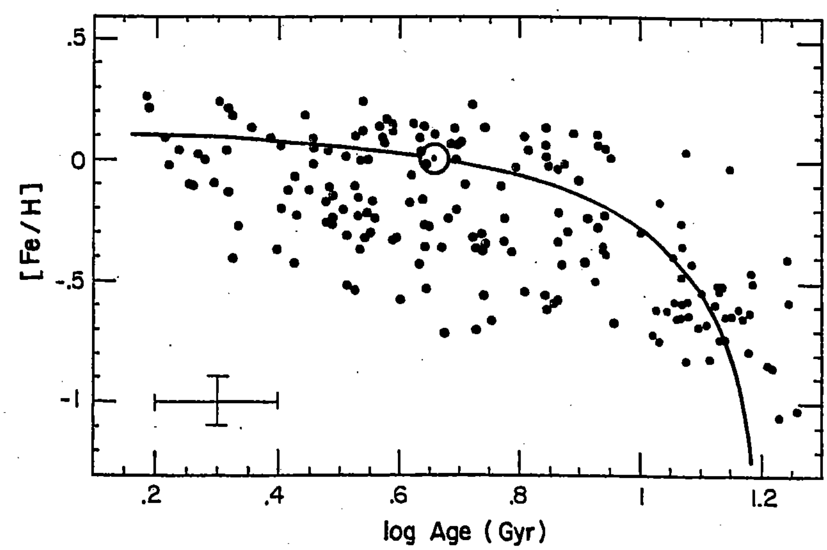
CCD image of a disk around Beta Pictoris (1984). Research undertaken since overy indicates that one or more planets may be present in the disk. Courtesy Jet Propulsion Laboratory.

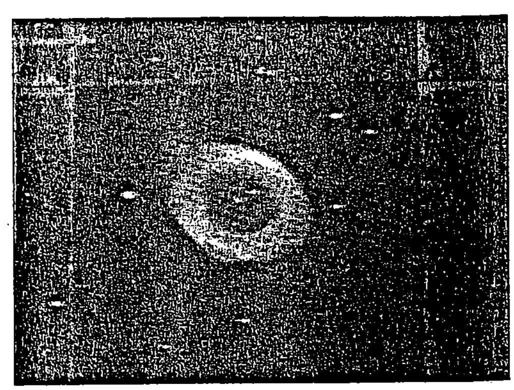
The story of the history of detection of extrasolar planets has been an emotional and scientific roller coaster. Time and again, beginning about 1945, it has been announced that a planet outside of our solar system has been detected, only to be questioned, and discarded. The tide turned in the late eighties, with the discovery of a planet with a mass about 10 times that of Jupiter, orbiting around the star HD114762 at a distance of about .33 AU from the star. Subsequently, the planet detection rate has improved rather dramatically starting the mid-nineties. There is some disagreement still about the characterization of a few of these stellar companions as planets; but it seems safe to say that 25 or more planets outside our solar system have now been detected. In fact, there seem to be three stars around which we can actually conclude a planetary system, meaning more than one planet has been concluded in orbit around the star (USA Today, January 2001). I should mention that the planet nearest to Earth that has been detected is around the star Gliese 876, about 15.5 light years away from Earth.

Despite the renewed enthusiasm marked by a spate of planetary discoveries since the mid-nineties, some unexpected anamolies have been observed. The first, which actually is not really an anamoly, is that the detected planets are huge, not just in comparison to Earth, but even in comparison to Jupiter. About 85 to 90% are heavier than Jupiter, sometimes by a factor of 6 to 10. Most astronomers think that this is most probably not an anomaly, because we will naturally detect the largest planets through the indirect methods being used by us. However, a disturbing finding, with a consequence on the extraterrestrial life issue, is that these gigantic gaseous planets are orbiting way too close to their parent stars. Just to give one example, a planet 6.5 times as heavy as Jupiter is orbiting at a meager distance of .45 AU around 70 Virginis, sixty light years away from Earth. A third extraordinarily surprising finding is that we are finding planets in the oddest environments, for example planets around pulsars; it is not realistic, it seems, that these planets have any chance of harboring life, as they would be constantly bombarded by radiation, including the lethal gamma ray radiation.

At this point, it is necessary to discuss the mega-Jupiters in close orbit in a bit more detail. They are an anamoly because the theory that planetary scientists entertain does not envision such gaseous supergiants so extremely close to the parent star. Astronomers think that these supergiants may have formed in the outskirts of the solar system, like in the case of our sun, and then experienced an INWARD ORBITAL MIGRATION. A few different theories have been proposed on how such an inward migration may occur. The two popular ones are that the dust grains pulled the supergiants in through a forceful drag or that the supergiants migrated inside due to collisions or near-collisions with bodies of comparable size. Now, whatever the reason for a possible inward migration by these supergiants, for the extraterrestrial life issue, the question that has arisen is whether any possible rocky Earth-like planets can stay in stable orbit under the presence of the supergiants in extreme proximity to the parent star. Many astronomers suspect that they cannot, as they will be pulled in and collide, or get altogether ejected. This has a negative impact on finding rocky planets favorable to life within a habitable distance from the parent star.

Perhaps we should end this discussion on detection of extrasolar planets on a happier note. The Jet Propulsion Laboratory of NASA reported in 1983 that infrared satellite observations suggest that a disk of particles exists around Vega, a star in constellation Lyra. This was of course exciting news, because disks around stars inevitably lead to the possibility of planets in the stage of formation. The most spectacular instance of this phenomenon was discovered around Beta Pictoris in 1984, and the very recent images by the Hubble space telescope show the disk around Beta Pictoris to be quite thin, suggesting that planetary formation may be well on its way, or may have occured. Such proptoplanetary disks have now been observed around other stars, causing astronomers to hope that planet formation may be a relatively common feature around stars. But how about habitable planets? I now turn into that fascinating question.





The Ring Nebula, M57, in the constellation Lyrae, the Harp, is an example of a planetary nebula. It is visible in even modest telescopes on a summer night. (NOAO)

Metallicity *vs* age for a sample of nearby F and G-type stars, adapted from Edvardsson *et al.* (1993). The curve is based on Eq. (8.16), normalised to the Sun and with an assumed age for the disk of 17 Gyr. Nissen & Schuster (1991) give the corresponding relation for high-velocity stars.

2.2.4 HABITABLE PLANETS AND CONTINUOUSLY HABITABLE ZONES

It is not possible to give a precise definition of what makes a habitable planet, because evidence now accumulated on Earth clearly suggests that life, once it arises, can adapt itself to the most stringent circumstances. However, the evidence of such resilience is for the very lowest forms of life, such as extremophiles that are known to exist in deep ocean hydrothermal vents. For higher life forms, we can identify, taking Earth as a model again, a number of important factors for their sustenance over a very long period of time. These factors, the experts agree, most probably act in a very complicatedly correlated way, which is certainly not well understood. Nevertheless, we can say quite a few things with confidence.

Based on these minimum requirements for continued sustenance of higher life forms, we can tentatively define a habitable planet as one with a continuously comfortable surface temperature, continued existence of water in liquid form, a continuously retained viable atmosphere, and a constantly available source of energy. These factors are related to the planet's distance from the parent star, but habitability is much more than just the right distance from the star. For example, it is thought that certainly Mars, and probably even Venus, was at the right distance from sun at times in the past for life to exist, but no one thinks that any high life forms exist or have existed in the last several billion years on Mars. In other words, the complicated interplay of the various habitability factors made Mars, as well as Venus, inhabitable in a geologically rapid amount of time. In this sense, all the things seem to have worked out just right for Earth, and many experts worry that it is difficult to keep a planet, that is first of all at the right distance, continuously habitable for a long time, the kind of time periods that an Earth-like slow evolution would entail. Let us look at the different factors that experts think kept Earth habitable over a geologically vast period of time.

A. COMFORTABLE SURFACE TEMPERATURE

Although water will exist in liquid form in the temperature range 0 - 100 degrees centigrade, temperature above 50 degrees centigrade on a regular basis will make survival of higher life forms as on Earth impossible. On the other hand, one does not need the temperature to be always above freezing point; it is obviously not so on Earth itself. As long as temperature remains above freezing point for a sufficient proportion of time so that ice can get a chance to melt, and as long as it remains at a comfortable level most of the time, higher life forms should be able to adapt and survive. Somewhat arbitrarily, let us define the permissible temperature range as -10 to 60 degrees centigrade, that is 263 to 333 in the Kelvin scale. We can now ask the question what distance range around a star keeps the temperature within this range? If a planet is too close to its star, it will get too hot, while if it is too far, it will get too cold, and in either case the temperature will get outside of our permissible range.

This distance range can be computed by applying a well known formula. If the parent star is of luminosity L, and if a planet has surface temperature T, then the distance r is given by

$$r^2 = L/(4\pi\sigma T^4) \tag{2}$$

where σ is the Stefan-Boltzmann constant, L is in watts, and T is in Kelvins. The numerical value of σ is $5.67051 \times 10^{(-8)}$. Equation (2) will produce the distance r in meters, which can be reexpressed in terms of AU (astronomical unit, the distance of Earth to sun) on using the fact that 1 AU $= 1.495978707 \times 10^{11}$ meters.

It might be intellectually interesting to calculate the permissible distance range by using equation (2) for a few stars. For Bernard's star, which was suspected to have planets at one time, has a luminosity of 1.6918×10^{23}; substituting into equation (2) gives the permissible distance range in which surface temperature of a planet could stay at the comfortable range to be .029 AU to .047 AU. This is a very very narrow range, and it is natural to think that just probabilistically, it may be unlikely that a planet will form in such a narrow range. For tau Ceti, which has been one of the prime targets of the SETI movement, first by Frank Drake himself and later with radio telescopes at Nankay, the distance range works out to .96 AU to 1.54 AU. This is a wider range. But actual observations do not indicate any planets in orbit. The examples indicate that the permissible range or the habitable zone around many potential stars may be rather narrow. Let us now see why actually it is even narrower!

B. CONTINUOUSLY HABITABLE ZONE

Although equation (2) gives a range for a planet's temperature to be in a comfortable interval, the comfortable zone around a star actually changes with time simply because a star's luminosity changes with time. More specifically, the luminosity of a star increases with its age, and so equation (2) says that the comfortable distance range shifts outward with time. A distance range that stays comfortable over a geologically long period of time, such as 5 billion years, is now popularly known as a continuously habitable zone (CHZ). This range, obviously, is substantially narrower than the zone habitable at a particular time, say now. Although one can only make educated guesses, for our sun, the CHZ may be as narrow as .95 AU to 1.2 AU. Notice that Venus, at .72 AU and Mars at 1.52 AU, are both outside of this CHZ. In addition, this figure suggests that if Earth had formed just about 5 to 10% closer to the sun, higher life forms may not have had time to evolve. Very interesting material and calculations on the CHZ around stars can be seen in Kasting, Whitmire and Reynolds (1993). I personally also recommend the excellent presentation in Jakosky (1998), chapter 16. To put it plainly, unless a planet is within the narrower CHZ of its parent star, rather soon on a geologic time scale, its water might either vaporize or permanently freeze, just as it has happened on Venus and Mars. So how is it that we on Earth were so remarkably lucky in keeping our liquid water and most of all the spectacular oceans for such a long time? It is that question that I go into next.

C. THE CREATION OF THE OCEANS

By all accounts, the oceans on earth are a major, if not the pivotal, reason that life could arise and flourish for such a long time. Many of the most important questions about our oceans have not been answered without doubts. How did the oceans get created? Why did the oceans last for such a long time? How did the oceans maintain a stable salinity over such a long time? And how did the oceans contribute to our remarkable fortune in maintaining a healthy atmosphere for such a vast period of time? On our Earth, each of these factors was instrumental in the long evolution of life, and as such are important factors in analyzing the fundamental Drake equation.

So first let us enquire into the creation of the oceans. Actually it is misleading to talk about the creation of the oceans as they are today; there is no doubt that the early oceans were significantly different in chemical character from what they are today. It is thought that the early oceans may have formed in a combination of ways. First, sedimentary rocks in Greenland have been found that are dated 3.8 billion years old. Since this implies that water existed on Earth's surface at that time, it seems that the early oceans had formed at least 3.8 billion years ago. Now till about 3.8 to 4 billion years ago, Earth was experiencing massive bombardment from comets and other bodies from the outer space. The comets, in particular, had a substantial supply of ice, and because of this coincidence of the composition of comets, the period of the external bombardment, and the apparent creation of the oceans at around the same time as the bombardments, it is thought that part of the water that constituted the early oceans actually came from outside, that is, the comets. However, that is not the end of the story. The creation of the early oceans also has something to do with the early atmosphere and outgassing from the Earth's interior. In one scenario, the early hot atmosphere contains water molecules, along with carbon dioxide, and it cools quite quickly. The water molecules condense and form the early oceans. In a second scenario, there is an early hot atmosphere with carbon dioxide, but no water. The earth's interior, on the other hand, has an abundant supply of certain minerals known as hydrates. Since the interior is very hot, the chemical bonds in the hydrates break apart, causing the water molecules to escape. The water now leaks through from the Earth's interior and creates the oceans. It is difficult to reconstruct which, or if both, of the scenarios were responsible for the origin of the oceans. It is worth noting that if cometary origin or the leakage theory holds, then it should not be that difficult for liquid water to originate in some other planets, and in fact the evidence is now very strong that oceans of liquid water had existed at some time in the past on Mars. A question of even greater significance is how the oceans survived to this time on Earth, while they disappeared on Mars, and the surface of Venus is also completely dry.

The answer lies in a captivating story of the interplay of the oceans, the atmosphere, and plate tectonics.

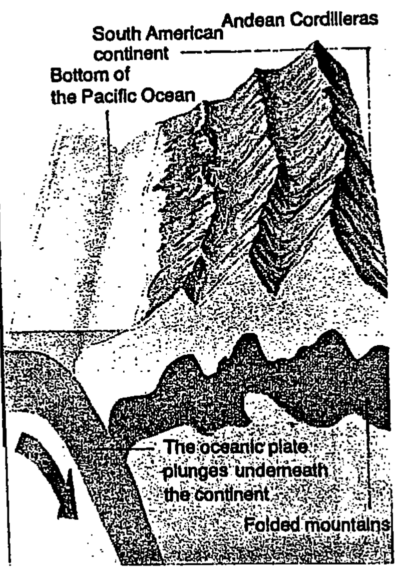
D. SURVIVAL OF THE OCEANS TO PRESENT TIME

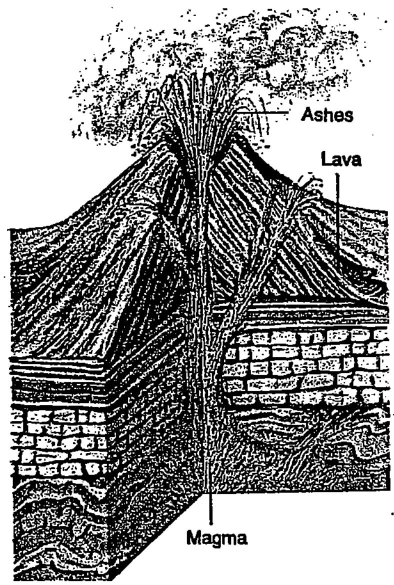
To fully appreciate the unique nature of our Earth in preserving its oceans, let us first note that we now have nearly indisputable evidence that an ocean of water existed on Mars in the geologic past, and disappeared. While on Earth, the oceans cover about 70% of the surface area with an average depth of about 12,500 ft., on Mars the oceans may have covered about one-third of the Martian surface with an average depth of about 5,500 ft. Why did it disappear?

The early atmosphere in our Earth was very rich in carbon dioxide. Carbon dioxide and other such greenhouse gases help in trapping the heat. With the sun getting increasingly brighter, and this preponderance of carbon dioxide in the atmosphere, the oceans would have soon disappeared, but for a beautiful interplay between the crust of the Earth, the oceans themselves, and the atmosphere. The carbon dioxide in the atmosphere reacted with the calcium in the rocks of the early crust to make calcium carbonate, which started to deposit in the ocean bed. This essentially produced a net small greenhouse effect, not so large that the oceans would have vaporized.

However, if most of the atmospheric carbon dioxide got removed and deposited at the bottom of the oceans as calcium carbonate, the planet would have cooled all too quickly, as it happened on Mars, and the oceans would have frozen. At this stage, another fortunate fact about the lithosphere of Earth came to the rescue. Unlike the Martian crust which consists of a single plate, Earth's lithosphere consists of an assembly of plates that actually laterally slide against each other. The major tectonic plates for Earth are the plates of Africa, Antarctica, Arabia, Australia, Caribbean, Cocos, Eurasia, India, Nazca, North America, South America, Juan de Fuca, Philippine, and the Pacific plate. In any case, due to the sliding lateral movement (as opposed to simply vertical movement), the deposited carbonates are slowly dragged to the subduction zones, and sort of drop into the Earth's mantle. The heat in the mantle causes the carbon dioxide hitherto imprisoned in the carbonates to be freed, and they come back to the atmosphere through ongoing volcanic activity. This is how the extremely delicate carbon dioxide balance was maintained, keeping the oceans from either boiling away due to excessive carbon dioxide or freezing due to loss of all carbon dioxide.

Colliding with the South American plate, *and plunging underneath it, the Pacific plate causes folding of the crust into mountains: the Andean Cordilleras.*





***Magma** erupting through the vent and the flanks of volcanoes is basalt, that is, molten rock.*

Rather interestingly, not only the oceans survived but in fact their salinity and chemical composition have also remained remarkably stable since the last 2 billion years. The importance of this stability to marine life is not to be underestimated. Salinity of our oceans, measured in grams of sodium chloride per kg. of seawater, is about 34.5 parts per thousand. It varies, generally within a narrow domain, depending on latitude and separation from open oceans. Typically, salinity is lower in places where a rich supply of ice-melted water or freshwater are available, and it is lower in areas with high latitude. As with the phenomenon of the preservation of the oceans themselves, the stable chemical composition is caused by a near perfect balance between accumulation and elimination of continental sediments and debris. The salinity of the oceans would be much greater today if there was not an equalizer in the form of removal of salts with the minerals. One can ask why such a spontaneous and exact balancing process should exist over such a long period of time, separate from asking what is the mechanism of the process. I have not found a satisfactory answer.

Previously we witnessed how the existence of plate tectonics in Earth was the key contributor to the long term preservation of the oceans by helping keep the all important carbon dioxide balance in the atmosphere. But what about oxygen, that precious substance all animal life depends on? How did we preserve the oxygen and the atmosphere? Let us talk about that next.

2.2.5. LONG TERM RETENTION OF THE ATMOSPHERE

Earth is the only planet in our solar system that developed a friendly atmosphere and was able to retain it over billions of years. The other three terrestrial planets, Mercury, Venus, and Mars do not have or never had a friendly atmosphere. Why was Earth so fortunate?

Perhaps we can best appreciate the ability of Earth to retain its atmosphere by first discussing why the other three terrestrial planets failed. In the case of Mercury, it is so small in size and so close to the sun, that it had practically no chance to hold on to an atmosphere. The small size gave it a very weak gravitational strength; and proximity to the sun gave it excessive heat and exposure to strong solar winds, both of which contributed to the loss of any atmosphere.

Venus, on the other hand, does have an atmosphere. It is just that it is unbearably thick. The culprit in the case of Venus was the planet's inability to remove the carbon dioxide, which, in the case of Earth, was made possible by the oceans. Thus Venus underwent a massive greenhouse gas effect, and its surface temperature soared. Venus now has a surface temperature of about 875 degrees Farenheit; one can see the importance of keeping the greenhouse gases in control.

How about Mars? In the case of Mars, contrary to Venus, the atmosphere is too thin. It is generally believed that in the past Mars had a much denser atmosphere; how was it lost? There could be several factors. One possible factor is that like Mercury, Mar's gravitational field is also quite weak. But many scientists think that the near absence of a magnetic field may have also resulted in the gradual loss of the Martian atmosphere. The maximum dipole magnetic field in Mars is less than .01% of that of Earth. Consequently, solar winds have been eroding the Martian atmosphere continuously over time.

In the case of Earth, none of these unfavorable factors weighed in. It is not too close to the sun, not too small, was able to maintain the carbon dioxide balance, and has a nice and strong magnetic field! But all that still does not explain free oxygen and its retention in the atmosphere. Let us briefly discuss that nice turn of events.

Earth's atmosphere is made of five layers, the troposphere, the stratosphere, the mesosphere, the thermosphere, and the exosphere. The atmosphere we talk about is concentrated in the troposphere, extending to about 10 miles at the equator and 5 miles at the poles. The present day atmosphere contains 78% nitrogen, 21% oxygen, .93% argon, .03% carbon dioxide, and a multiple of other substances in lesser or small amounts. The ozone layer, which filters out the sun's ultraviolet rays, is in the stratosphere, and has been showing signs of depletion during springtime.

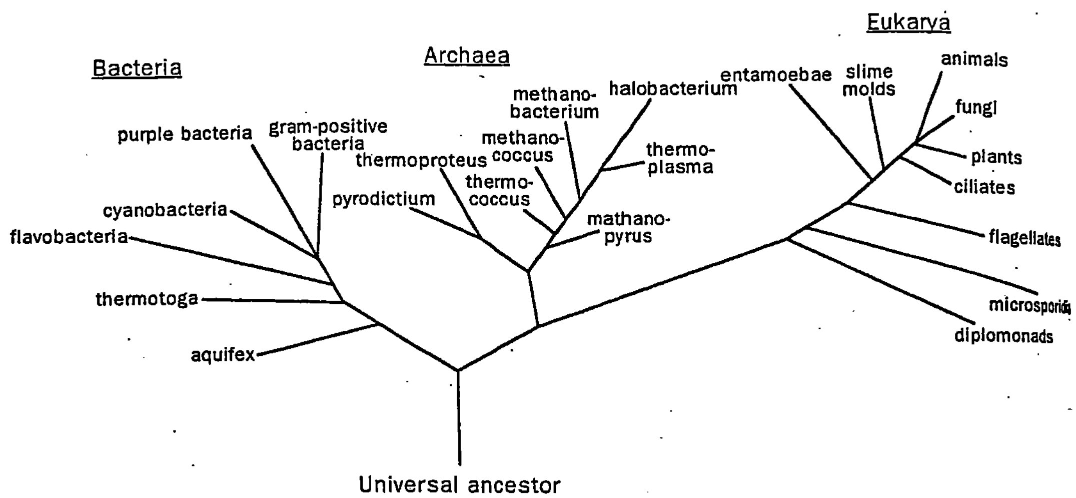
Thus, free oxygen is available in a very significant percentage in Earth's atmosphere. But it was not so in the beginning. Where did it come from? To understand this, we have to have some understanding of the primitive atmosphere in Earth and its evolution. The details are not clear and in particular, whether the atmosphere at the time life was beginning to take its foothold was reducing or not is a point of contention.

The atmosphere was formed by degassing of the interior. The atoms available at that time that could be used to make an atmosphere were the atoms of hydrogen, helium, oxygen, neon, nitrogen, carbon, sulphur, and argon. Hydrogen atoms were in the greatest supply and helium atoms next, roughly 90% and 9%. Helium, neon, and argon are chemically inert and did not form any combinations. Thus possible combinations were formed by the hydrogen, oxygen, nitrogen, carbon, and sulphur atoms. Of these, oxygen combined with hydrogen to form water; nitrogen and hydrogen gave ammonia; carbon and hydrogen gave methane; and sulphur and hydrogen gave hydrogen sulphide. The ammonia, methane and hydrogen sulphide molecules were pulled back by Earth's gravitation and water vapor was contributed by the oceans. The rest, for the most part, escaped into outer space. So we do not yet have free oxygen.

Free oxygen starts to develop when the molecules of water vapor break into hydrogen and oxygen atoms. The oxygen atom, much heavier than hydrogen, would be held, while the hydrogen atoms would escape. The highly reactive nature of oxygen now causes the oxygen atoms to group with hydrogen atoms in ammonia and methane and hydrogen sulphide to reproduce water; the nitrogen atoms stripped off from ammonia stay single as they are not reactive; carbon atoms from methane combine with oxygen to give carbon dioxide, and sulphur and oxygen give some sulphur dioxide. The sulphur dioxide mostly gets removed by reacting with continental rocks and getting dissolved in the seawater. Of course, carbon dioxide does a similar thing too, but gets recycled through volcanic activity, as we saw before. This gives an evolved atmosphere of nitrogen, carbon dioxide, water, and some residual free oxygen, but not plenty. This is starting to look like the atmosphere today, but we have got more explaining to do.

Over the last several billion years, the abundance of carbon dioxide in the atmosphere has decreased and that of free oxygen has increased. According to some theories, the abundance of free oxygen has increased by a factor of 10,000 in the last 3 or 4 billion years, with the sharpest rate of increase around 2 billion years ago. Interestingly, that is the estimated time that photosynthetic bacteria and the simplest plants in the oceans started to release extensive amounts of free oxygen as a byproduct of photosynthesis. We thus see that the friendly atmosphere of today with its abundant supply of free oxygen is itself an output of life, and the associated biological activity.

I now go into that greatest question of all: how did life begin?



2.2.6. ORIGIN OF LIFE ON EARTH

Film director Woody Allen once said: "anything worth knowing cannot be understood." The mystery of the origin of life may be one such. Although fossil evidence cannot prove so, scientific minds are converging on the consensus that life already existed on Earth 3.8 billion years ago. Living organisms on Earth have a preference for light carbon. The oldest sedimentary rocks that have been dated are 3.8 billion years old; these are the rocks from Isua in Greenland. Quite interestingly, these rocks show an excess of the isotopes of the lighter carbon. Scientists think that this is the evidence of the earliest life on Earth. We mentioned before that Earth was experiencing bombardment by objects up to several hundred kms in diameter till 4 billion years ago. It seems that it would have been impossible for life to emerge under such conditions. The conclusion is that life arose on Earth, almost as soon as it was theoretically possible, after the massive bombardments stopped. The enigmatic transition of dead matter to living matter had taken place. How and where was this barrier crossed? The truth is although milestones have been achieved in setting out theories and conducting experiments to explain the origin of life, the answer remains an elusive mystery. In the next few paragraphs, let us try to understand the history of the experimentation and the theories to explain this singular event on Earth.

A. WHAT IS LIFE

Actually defining what is meant by life is a frustrating act; we can intuitively characterize most things as being living or not living, but we are hard pressed to give a precise definition. We would like to describe life as a collection of complex organic molecules, such as enzymes and other proteins, within the safe environment of cells, that can utilize energy from a suitable external source, and reproduce and multiply by transferring genetic information from the mother to a daughter cell. For all Earth life, the genetic information is stored and transferred by the use of DNA and RNA molecules. An interesting example in trying to define what is alive is a virus. Viruses make copies of themselves by reprogramming a host cell; although they do have DNA, they cannot reproduce themselves. Examples such as this illustrate the difficulty in giving a real definition of life that will apply without ambiguity to all cases. However, the three main steps we wish to explain are the formation of cells, organization of the simple organics into complex organic molecules such as enzymes and proteins, and the origin of the genetic apparatus involving the DNA and RNA molecules. The origin of life question is so complicated because it is not known how each of these three steps were achieved, and what was the order of the steps. Nevertheless, it is undoubtedly instructive to go into a brief examination of what the experts think.

B. THEORIES ON POSSIBLE PATHWAYS TO LIFE

Freeman Dyson, in his provocative writing "Origins of Life" (1999) says: "Concerning the origin of life itself, the transition between lifeless chemical activity and organized biological metabolism, there is no direct evidence at all. The crucial transition from disorder to order left behind no observable traces. When we try to understand the nature of this transition, we are forced to go beyond experimental evidence and take refuge in theory." Let us see some of the attempts that have been made to explain the three steps and what the difficulties are in accepting these theories as the correct explanation.

Synthesis of Complex Organic Molecules

We would like to understand how extremely complex molecules of protein or nucleic acid could have formed starting from a disorganized array of biogenic elements. How can the simple molecules in an abiotic Earth having two, three, or five atoms organize themselves into enormously more complex molecules made up of thousands of atoms?

An explanation is that simple molecules may build into complex ones if they get excited by a source of energy. About 50 years ago, a by now famous experiment helped illustrate how such a thing can happen, to some extent anyway. In 1954, Harold Urey and Stanley Miller, subjected a solution of water, hydrogen, ammonia and methane to an electric "shock" and basically let it sit for a week. Urey and Miller noticed at the end of that one week that complex organic molecules had formed inside the flask. Precisely, molecules of the two simplest amino acids, glycine and alanine, had formed. And proteins, after all, are long chains of amino acids linked together by peptide bonds. This would point to the tantalizing possibility that the building blocks of life can be constructed by starting with a haphazard array of simple but mutually reactive organic molecules, and subjecting them to water, and energy.

The Urey-Miller experiment can be thought of as an experimental support for the Oparin-Halden theory for the origin of life. About thirty years prior to the Urey-Miller experiment, Russian biochemist Aleksandr Oparin and versatile English scientist J.B.S. Haldane had suggested that organic molecules would have formed in the prebiotic hydrogen-rich reducing atmosphere of Earth, and combine to form increasingly larger complex organic molecules, which would form semi-living things such as viruses, which would evolve into cells.

In the fifty years since the Urey-Miller experiment, this thesis has come under scrutiny and serious questioning. First, the relevance of the Urey-Miller experiment itself is now in question. Replications of the experiment always succeed in production of amino acids in a reducing atmosphere, even when the energy source is varied; but they never succeed in producing anything except virtually trivial amounts of amino acids in a neutral or oxidizing atmosphere. Geological evidence now suggests that around 4 billion years ago, Earth's atmosphere consisted of carbon dioxide, water vapor, and nitrogen; it was not reducing. Thus the very premise of the Urey-Miller experiment came into significant questioning.

How about prebiotic synthesis of nucleotides? Freeman Dyson (1999) explains why this is even more problematic. There are three parts in a nucleotide; an organic base, a sugar component, and a phosphate ion. The phosphate ion would have been available in rocks and the oceans; so we need to worry only about the other two components. The organic base can be synthesized out of a very concentrated solution of ammonium cyanide, in a hydrogen-rich reducing atmosphere; and the sugar from a similarly concentrated solution of formaldehyde, again in a reducing atmosphere. We find ourselves grappling again with the evidence that the prebiotic atmosphere was probably not reducing.

There is still another problem. Even if we can get the three components to synthesize, we still have to put them in the correct geometric order. And even if they are arranged in the correct geometric order, their natural fate would be to dissociate into their separate components. Thus, one needs a mechanism to produce them in such large numbers that adequately many of them can escape breaking down into their components.

Perhaps an even greater barrier to cross is the organization of very simple organic molecules into the immensely more complex protein or nucleic acid molecules. The theory is that simple organic molecules would be available rather easily, and they would come into random contact with each other. The chemical reactions will take place, and over time the reactions will lead to complex molecules. Of course, no one knows if that is what happened; but some calculations have been done to test the plausibility of such a scenario. Robert Shapiro, in Origins (1987), does a calculation on the chance of creation of a RNA with 20 nucleotides, assuming that a billion years was available. He calculates the chance to be something like $10^{(-992)}$. Forty years before that, Lecomte du Nouy, in his Human Destiny (1947), calculated that one simple protein molecule would take 10^{243} years to form from chance alone. In a philosophical mode, he comments that "these consequences lead inevitably to the idea of God."

We should be cautious not to get too pessimistic about the synthesis of proteins and nucleotides. They are here; absent the idea of an external master chemist, a divine hand, all we can conclude is that the process of synthesis could be one that the human mind has not yet thought of. We should also make a note that intriguing evidence for cosmic delivery of organic molecules is present. As many as 74 amino acids, 55 of which do not occur on Earth, have been found on analyzing carbonaceous meteorites picked from various places on Earth. In addition, a variety of organic molecules, including formaldehyde, have been found in the interstellar molecular clouds. There is now a substantial number of very respected scientists who do not rule out the possibility of a cosmic delivery of organic substances from outer space that would have been difficult to produce in a nonreducing atmosphere on Earth.

Cells and Cell Membranes

The word 'cell' in a biological context was first used by Robert Hooke, an English scientist, in the seventeenth century. All living things are made of cells. Animal cells consist of a nucleus containing hereditary material, the cytoplasm, a jelly-like substance in which the chemical reactions take place, and a membrane, which is not dissolvable in water, but allows entry and exit of materials, such as nutrients and waste products. Plant cells also have a rigid cell wall.

We can think of a cell as a volume enclosed by a boundary, that is the membrane. What precipitated the formation of a membrane? Are there any known plausible methods in which a membrane may have been created? There are some theories. First, membrane formation is apparently not very difficult. If amino acids are put together in water and heated, they would often form a microsphere with a thin membrane.

But what caused the formation of an enclosed volume protected from the outer environment, something we can call a cell, in the first place? Isaac Asimov (1987) describes a theory. Here is how it goes. By whatever means, the warm ocean of 4 billion years ago contained a large amount of complex organic molecules. These still do not meet the definition of a virus, but something short of a virus. These semiviruses continue to grow in number, and a competition ensues for a supply of energy. Those that can form a protective shell that will hold the "food" inside, which presumably was the seawater with the organic compounds itself, would have a competitive advantage. This would cause the formation of an enclosed volume with a thin protective shell, something resembling a cell.

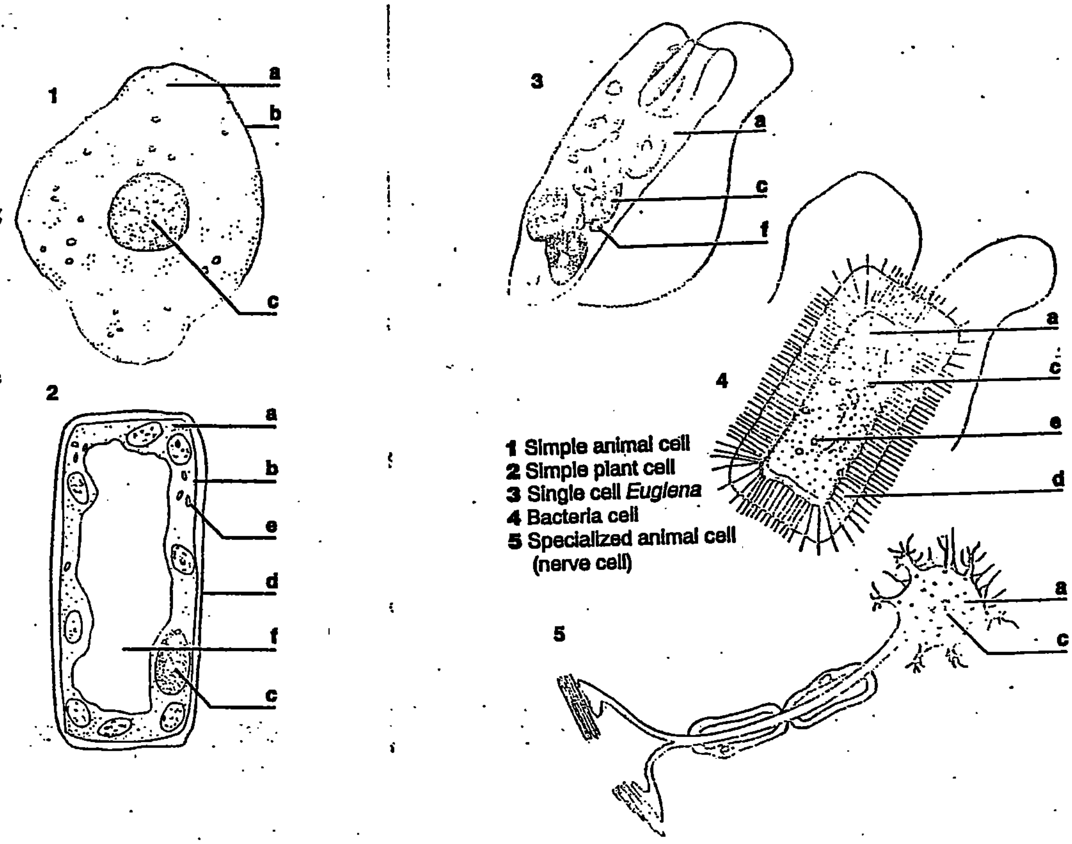
The Genetic Apparatus: DNA and RNA Molecules

In all terrestrial organisms, hereditary information is transferred by using DNA and RNA; the chemistry involved is very very complex. DNA stands for deoxyribonucleic acid, and RNA for ribonucleic acid. These are macromolecules of nucleotides. The DNA

The form of life known on Earth *is based on the chemical structure of carbon. This diagram shows duplication of DNA (deoxyribonucleic acid), a long chain of complex molecules that allows the transcription of genes.*

CELLS

Living things are made of cells. Animal cells (1) and plant cells (2) share some characteristics of cells, although, in any plant or animal, the cells are specially developed to do certain jobs. All cells contain the following elements:
Cytoplasm (a) a transparent jelly-like substance, in which the chemical reactions of life occur.
Cell membrane (b) a skin around a cell which allows the entry and exit of materials.
Nucleus (c) the cell's control center, containing hereditary material (chromosomes).
Plant cells have additional features. These are:
Cell wall (d) outside the membrane, this gives the cell rigidity and shape. It is made of cellulose, a non-living substance.
Plastids (e) units involved in making and storing food.
Vacuoles (f) large cavities containing air or fluid. Many plant cells have one large vacuole.



molecule consists of two strands of nucleotides, running sort of against each other in a spiral, with each turn in the spiral consisting of ten nucleotides. The popular term "the double helix of DNA" derives from this double chain in the spiral ribbon. Each nucleotide has a phosphate-sugar section attached to a base, adenine (A), cytosine (C), guanine (G), or thymine (T). The bases on the opposite chains are linked together by a hydrogen bond, and the pairings are sharply defined; A pairs with T, and C pairs with G. The RNA molecule is simpler in form, as it has only one strand, and the sugar and the organic base are also different. The duties of DNA and RNA molecules in the genetic apparatus are also different. Genes are (long) sequences of these nucleotides on a DNA molecule, and each chromosome, inside the nucleus of a cell, contains many genes. The hereditary traits are determined by the genes.

Thus the three steps that we wished to explain before, protein, the cell, and the genetic apparatus, are functionally related together in the following way. Genetic information is coded into a DNA molecule; the RNA molecule converts this information to proteins; the proteins are used to create cells; and the cell nucleus contains the chromosomes that house the DNA molecule.

There are several extremely difficult questions to answer. What is a plausible process for creating the highly complicated DNA and RNA molecules? Which came first? Between the genetic apparatus and proteins, which arose first? As one tries to approach the questions, one is quickly engulfed in pretty serious paradoxes. The RNA molecule, as we saw before, is simpler than the DNA molecule. So let us pretend that it came first. But how does the RNA molecule reproduce? It cannot reproduce without the catalytic help from enzymes, which are particular proteins. But proteins are formed by using the genetic information conveyed by the RNA molecules. There is a contradiction.

A potential milestone was achieved when Thomas Cech discovered in 1982 RNA molecules that also act as catalytic enzymes; he called them ribozymes. So if it is true that autocatalytic RNA molecules did exist at that dawn of life, then we have may have a way out of the previously seen paradox: enzymes may not have been necessary. Nobel Laureate Walter Gilbert introduced the phrase "RNA World" to propose that in the beginning, RNA alone was executing all of the functions of a cell. Gradually, over time, RNA was supplemented by DNA and the genetic duties of coding and transfer of information got divided.

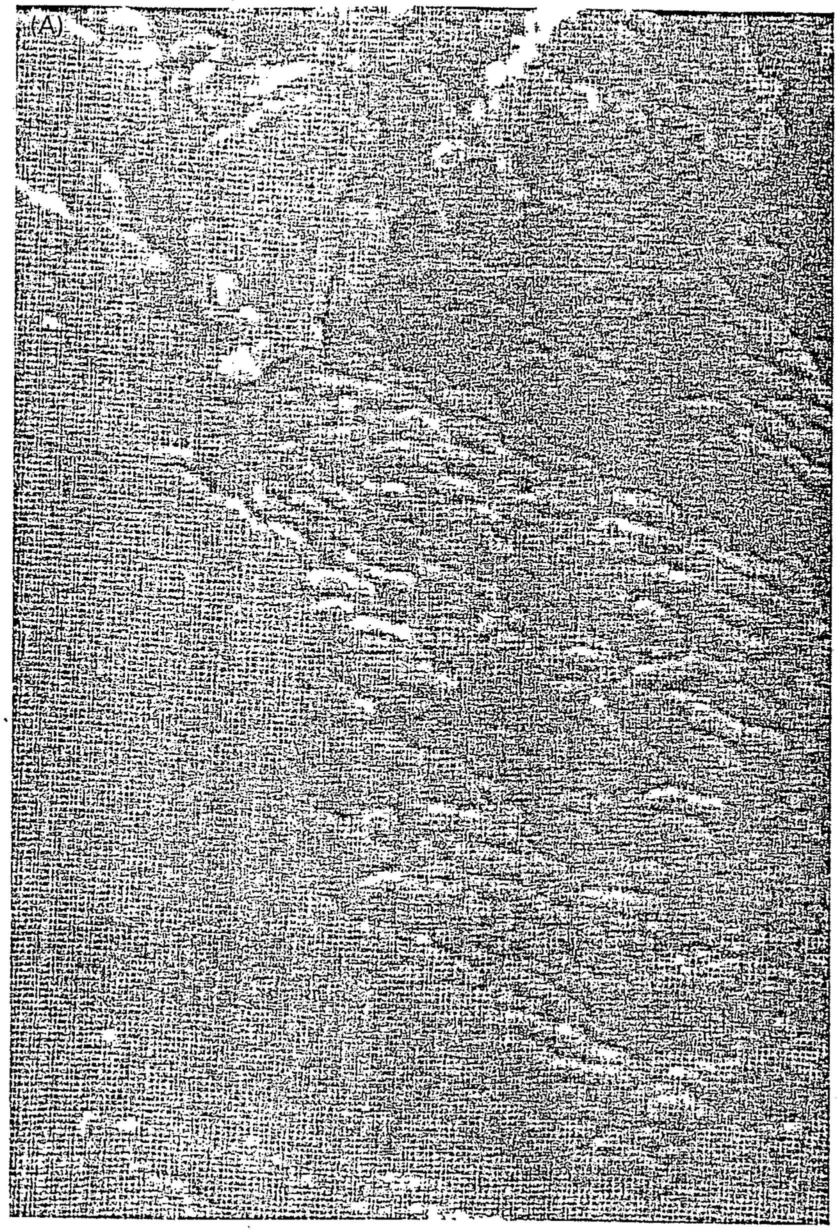
This theory appears to have gained solid acceptance by experts. However, it is worth mentioning that difficulties have been pointed out. It has not been possible to make ribozymes in laboratories by using RNA alone; the experiments use enzymes. Second, simulations of models in Niesert, Harnasch, and Bresch (1981) show that RNA molecules do not like to perform all the functions of a cell; they specialize themselves to one act.

To conclude, let me remind the reader of the question we asked at the outset: what was the order of emergence of proteins, the genetic apparatus, and the cell? No one knows.

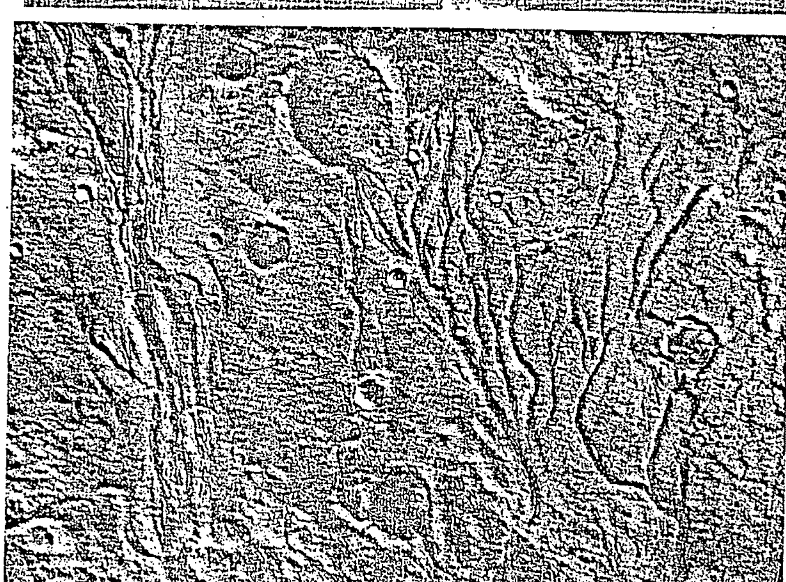
So by a process that is far from understood, life originated on Earth, about 3.8 billion years ago. Today, there are an estimated number of 10 to 30 million different species of life on Earth. Once it arose, life evolved into an incredible diversity, in water and on land, through thick and thin, in the most creative ways, resulting ultimately in Man, Homo Sapiens, about 100,000 years ago. It is that fantastic story of chance events and continual emergence and extinction that I now briefly turn to.

2.2.7. EVOLUTION OF LIFE

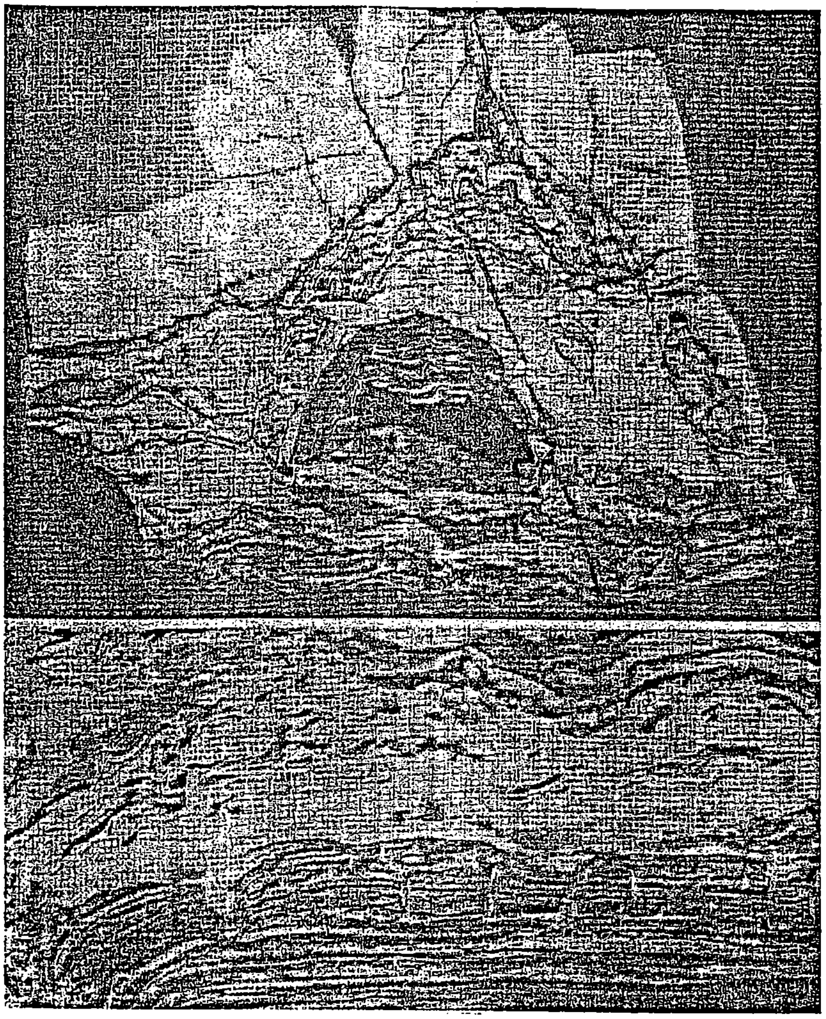
Life emerged, about 3.8 billion years ago, on Earth as a single cell, and flourished to its present day ravish diversity through evolution. The story of evolution of life on Earth through natural selection is remarkable; it is a story of punctuated but unambiguous progression to complexity and sophistication. The progression was undoubtedly marked by random events, which affected the path of the evolution. It is singularly unlikely that if the clock of time was let run once again, starting at 3.8 billion years ago, the pinnacle of sophistication of life on Earth would look like Homo Sapiens. Loren Eiseley (1946) said it eloquently: "Nowhere in space or on a thousand worlds will there be men to share our loneliness. There may be wisdom; there may be power; somewhere across space great instruments, handled by strange, manipulative organs, may stare vainly at our floating cloud wrack. Nevertheless, in the nature of life and in the principles of evolution, we have had our answer. Of men elsewhere, and beyond, there will be none forever." In the next few paragraphs, I will outline the evolution to complexity of the first life on Earth, and the forces driving this extraordinary process over eons.



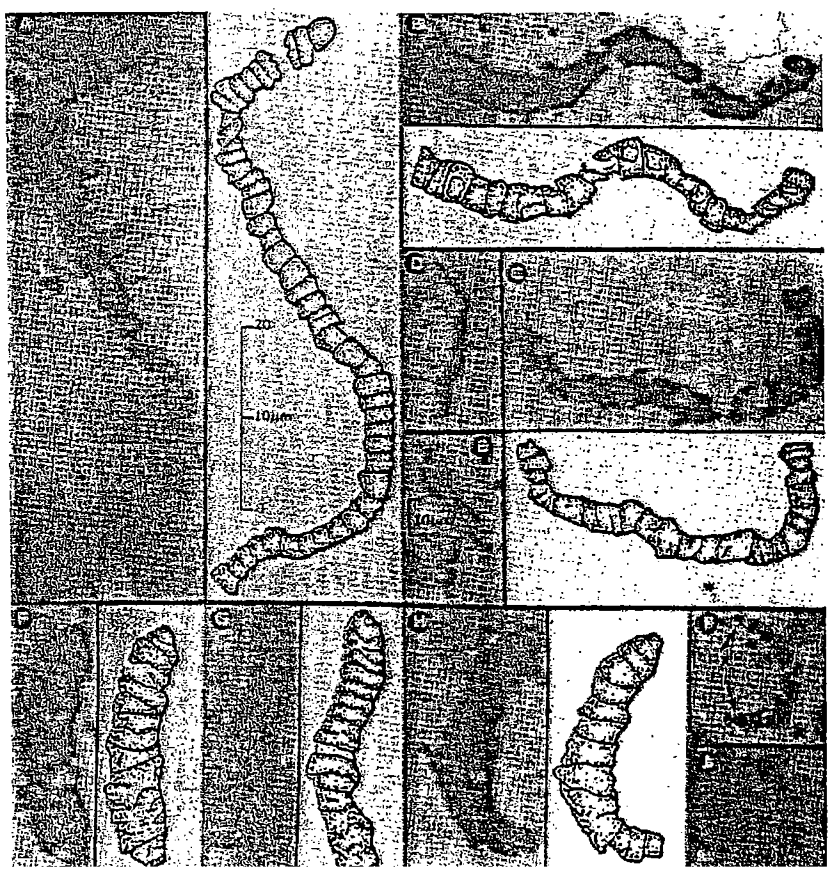
Examples of possible fossil martian bacteria. (NASA photos.)



River channels on Mars, probably cut by water seeping out from underground rather than by rainfall. These so-called 'valley networks' are in the old heavily cratered terrain in the southern hemisphere



Domical (top) and flat-laminated (bottom) stromatolite-like structures, found in rocks that a 3.5 b.y. old in the Warrawoona Group in Western Australia. The domical structure is about 30 cm across, and the flat structure is about 10 cm across. (Photo courtesy of J.W. Schopf.)



Fossil bacteria found in 3.5 b.y. old chert in Western Australia, shown along with interpretative drawings. Images D, E, I, and J are at the scale shown in E; all others are at the scale shown in A. (Figure courtesy of J.W. Schopf.)

With a very broad brush, the major steps in the evolution of life might be sketched as follows:

Time (billions of years ago)	First Appearance
3.5	Stromatolites
3.4	Prokaryotes
1.5	Eukaryotes
.6 - .8	Multicellular organisms
.5	Fish
.45	Land plants
.4	Animals
.25	Dinosaurs
.2	Mammals
. 15	Birds
.14	Flowering plants
.065	Advanced mammals
.055	Primates
.004	Hominids
.0001	Homo Sapiens

First, I should emphasize, appropriately, that the times of first appearance of the various groups are approximate; in two different authentic sources, one can easily see a difference of up to 300 million years. This is particularly true of invertebrates, for there is a deficiency in fossil records.

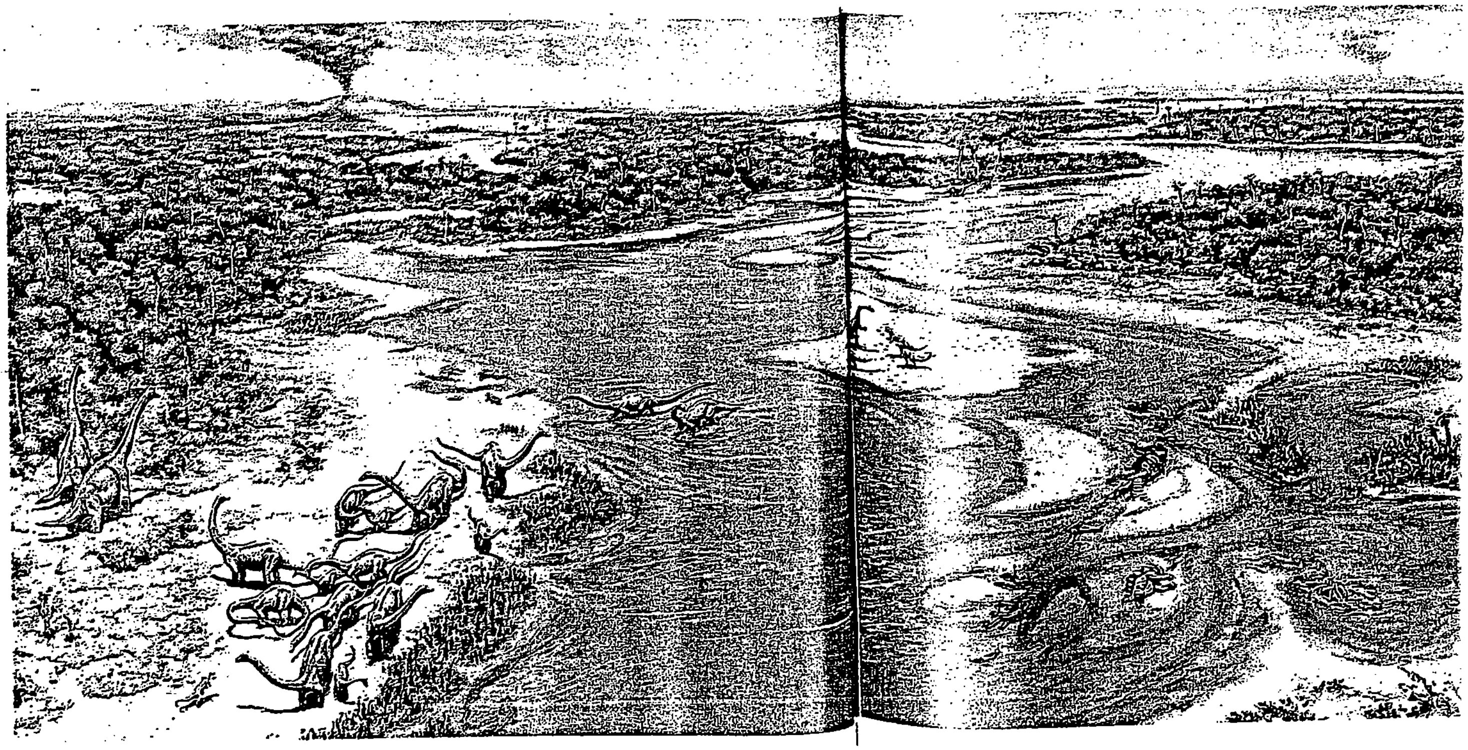
Stromatolites are layered sedimentary structures formed by bacteria; the most ancient ones have been found in Australia and South Africa. They are very very rare at present. Prokaryotic cells are bacterial cells without a nucleus. The word "Prokaryote" means "prior to the nucleus" in Greek. In spite of the lack of nucleus, the prokaryotes multiply. In fact, they multiply rapidly. Once they appeared in the life's scene approximately 3.4 billion years ago, they reigned for the astoundingly long time period of about 2 billion years, until the first eukaryotes or nucleated cells appeared. This was in fact a major step in life's evolution, for the first eukaryotic cells may have been 1,000 times larger in size and contained much of the fancy material we are familiar with today: DNA, mitochondria, ribosomes. And once they appeared, it took another three-quarters of a billion years before the next step in progression was achieved: appearance of multicellular organisms.

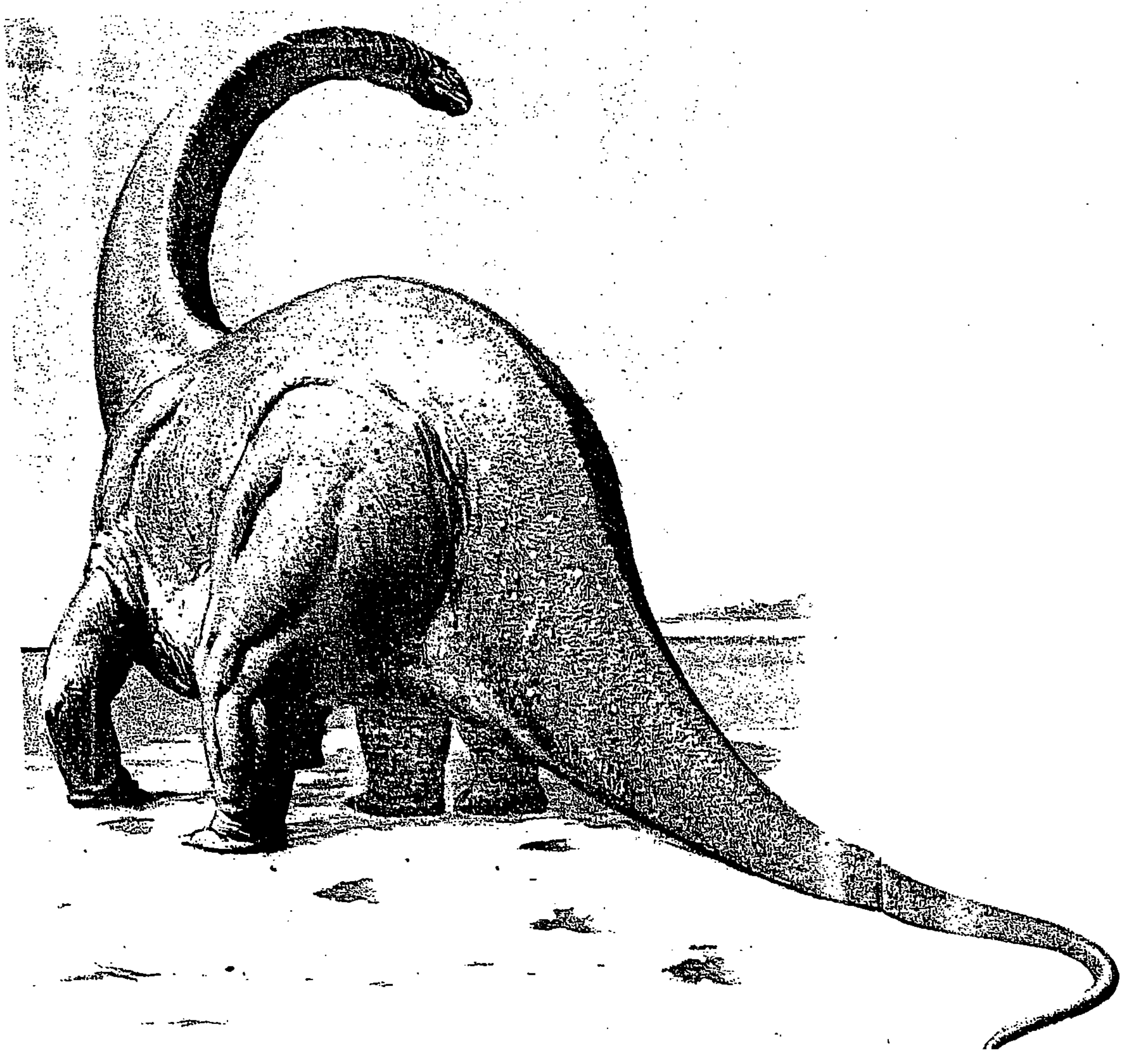
What were the selective factors responsible for emergence of multicellularity? It is conjectured (Bonner (1988)) that it might have been brought about by the need to break down large food particles and as a protective mechanism against predation. Multicellular organisms produce enzymes in a larger amount, an advantage in breaking down food; and multicellular organisms would be able to swim faster than a unicellular one, an advantage in escaping from a predator. It is also conjectured that if multicellularity was once obtained as an error, it might have been preserved just because it was found to be something useful. The oldest traces of multicellular life are about 600 million years old, pre-cambrian in time. These fall short of being fossils, because they correspond to soft-bodied multicellular organisms, such as jellyfish and sponge. The first fossils correspond to what are called arthropods, the primitive crustaceans, and then arrived the fish.

For approximately 3.4 billion years after its emergence, life on Earth remained confined to water. However, the competition among the different life forms became too stiff. It thus became necessary for sea life to adjust to land. The first vertebrates to invade land, on a part time basis if we may say so, were the amphibians. They would live part of the time on land, and return to the waters for laying their eggs. The first amphibians are dated to about 350 million years ago. This was a monumental step in the evolution of life, when we realize that the amphibians evolved into the reptiles which later evolved into mammals. Yet, the invasion of the land by animal life would not have been possible but for the gracious emergence of land plants, first. The existence and full fledged development of land plants as a dependable source of food for the animals was quite essential, before animals could invade the land. Land plants had already existed for the better part of 50 million years before a reliable food chain was in place for animals to start to live on land. Was the emergence of land plants a lucky break? And could animals arise and sustain at all without this event?

There is considerable uncertainty about exactly when animals first appeared. It has been suggested that the annelids had split from the chordates as early as 1 to 1.5 billion years ago. Most paleontologists seem to find this unbelievable. At any rate, it seems likely that fossil record does not correctly show the time of first emergence of the animals; we seem to have fossil records from the Cambrian era, associated with the famous "Cambrian explosion" of life, but none for the first and the simplest animals. The question has been asked if the cambrian blooming of animal phyla following the initial emergence of minute animals was inevitable. What were the forces and the stimuli behind the second, later, diversification? Several theories have been suggested. One theory is that the biological advancements were purely biological inventions and there were no external environmental stimuli. Others have a different opinion. The emergence of animals was marked by the formation of the continents. This had opened up a whole new, vastly unoccupied, habitat for life. The animals emerged in response to an ethical necessity to fill this niche. Others suggest that the emergence of the animals may be due to a rise in the level of atmospheric oxygen at that time. The first reptiles, on the other hand, appeared as the landscape changed to one of luscious vegetation and forests, with the setting in of the Carboniferous period, about 300 million years ago. The most notorious of the reptiles are the dinosaurs, mammoth beasts, that reigned on the face of Earth for about 185 million years. The earliest dinosaurs were actually quite small, about the size of a chicken, with scales. The largest ones were massive of course, some were up to 90 ft. long and up to 40 ft. tall. It is believed that the Brachiosaurus was the largest land animal in the history of Earth. The other gigantic ones include the Tyrannosaurus and the Brontosaurus. Then, about 65 million years ago, they disappeared.

It is now accepted that the principal cause for the extinction of the dinosaurs and indeed many other life forms around the K/T boundary in time was the impact of an asteroid (or a comet), 10 to 20 kms. across, and it is believed that the site of the impact was at the Yucatan peninsula in central America. The evidence that this was the principal reason for the vanishing of the dinosaurs is circumstantial, but strong. First of all, the crater at the impact site has been found. Second, examination of layers of rock, across the whole of Earth, shows an excess in the abundance of a rare element known as iridium by a factor of 10 to 25. Rock layers are a standard method to obtain geologic evidence as a function of time. And iridium, although rare as a terrestrial element, is in good supply in space. So a tremendous excess in the level of iridium in the same thin layer of rocks, spanning widely separated areas on Earth, is a very strong indication that an impact happened at that time, and it coincides with the time of extinction of the dinosaurs. The environmental effect of such an impact would have been simply catastrophic, in more ways than we can discuss here. Surface temperature would have risen dramatically; much of the water would have evaporated; the sunlight would have gotten completely blocked for a year or more, causing a 'nuclear winter'; the food chain and specifically, a lot of





Mark Hallett's painting *The River* shows what a Late Jurassic pterosaur might have surveyed as it soared above what is now Utah, assuming that flying reptiles had color vision. Lush vegetation thrived in what was then a hot, humid climate, and a large waterway would have attracted herbivores, with carnivores following close behind.

the plants would have gotten destroyed; global acid rain would have contaminated the remaining water; tidal floods would have caused destruction and loss of life; and a whole lot of organisms would have just gotten buried in the debris and the dirt from the massive impact. So even if the dinosaurs were already on their way to extinction due to other reasons, the Yucatan impact sealed their fate. And although the comparison is a stretch, just as things are very quiet, peaceful, and ready for a renewal, after a storm, when the dust cleared, Earth was ready for a fresh start on evolution. And arguably the most significant step in the evolution of life was made: the emergence of mammals.

Starting the end of the Cretaceous period, a diverse range of mammals made it into life's scene. Two major groups are the marsupials and the placenta mammals. The marsupials, the most charismatic representative of which are the kangaroos, did not blossom as much; the placenta mammals did better. They derive their name from the presence of a placenta that is used for diffusion of nutrients from the mother to the offspring's bloodstream. About 55 million years ago, a very special monkey-like squirrel made its appearance, the lemurs. The lemurs are regarded as the earliest ancestor of apes and monkeys, the primates, the sole bearers of an enigmatic characteristic, called intelligence.

The first human species appeared appeared about 2 million years ago, the Homo habilis; in only about 400,000 years they evolved into the next advanced human species, the Homo erectus; Homo erectus appears to have branched off into the Neanderthals and the Homo sapiens. The transition to Homo sapiens happened slowly, and the modern man appeared in Africa and Asia 100,000 to 120,000 years ago. The other branch, the Neanderthals, either got extinct or merged with Homo sapiens. Homo habilis had a brain about 800 cubic cms in size, and the technology was at the level of simple stone tools; Homo erectus had a slightly larger brain, about 850 cubic cms, and most probably knew the use of fire; the modern man has a brain approximately 1450 cubic cms. in size. The intermediate Neanderthalman actually had a larger brain than Homo sapiens, and in addition to use of quite sophisticated hunting instruments, had a culture, even if primarily in the form of rituals. The neanderthals existed till about 40,000 years ago. The exact sequence in which the modern man appeared is unclear. But since the Homo sapiens sapiens emerged about 100,000 years ago, it has learned the laws of the universe, developed languages and other communication skills, made a computer, and sent one of its own to the moon. This article is about the abundance of advanced species such as Homo sapiens sapiens elsewhere in this galaxy.

Although Homo sapiens may be characterized as the ultimate in complexity, increasing complexity was a constant companion of the entire evolution of life on Earth. How did evolution progress through an increase in complexity? How should complexity be measured? What were the forces of selection behind the emergence of increasing complexity? We now turn to that aspect of evolution for a few moments.

Years Ago	**Stages of Evolution**
4 million	*Australopithecus afarensis*
3.2 million	"Lucy" (*Australopithecus afarensis*)
2.5 million	several *Australopithecus* species
2 million	*Homo habilis*
1.6 million	*Homo erectus*
1.4 million	Australopithecines become extinct
1 million	*Homo erectus* settles in Asia
400,000	*Homo erectus* settles in Europe
	Homo sapiens begins to evolve
250,000	archaic forms of *Homo sapiens*
	Homo erectus becomes extinct
125,000	*Homo neanderthalensis*
100,000	*Homo sapiens* fully evolved in Africa and Asia
40,000	*Homo sapiens* (Cro-Magnon) fully evolved in Europe
35,000	Neanderthals become extinct; *Homo sapiens* remains the single surviving human species

2.2.8. THE EXTENSION OF COMPLEXITY

The history of evolution of life on Earth is marked by a steady increase in complexity. A bit like life itself, complexity can be felt but could be hard to define. It is easier to talk about the manifestation of an increase in complexity. For example, the invention of sex was an increase in complexity; and once invented, it was seen to be so advantageous, that it was retained. Increased complexity manifests in a variety of ways:

a. increase or in general change in size;

b. structural complexity through division of labor;

c. genomic complexity through an increase in amount of active DNA;

d. in higher animals, behavioral complexity through social and learning acts;

e. correlation between the various manifestations of complexity.

There has been a steady increase in the upper limit of the size of species in course of the evolution of life on Earth. It should be noted that the abundance of large creatures, percentage wise, has not necessarily increased. Animal abundance is larger at the small end of size; the increase in size in course of evolution has occured in the maximum size. Size increase has the advantage of avoiding predation; also, size increase up to a certain level means that the animal (or plant, etc.) can do a greater number of things, a progression. Size split, as opposed to just size increase, is a way to create two separate species, a method of diversification. But it should be noted that unchecked size increase is not beneficial to the species; larger species are susceptible to a quicker extinction.

Clearly, size increase has something to do with an increase in the total number of different cell types. At the lowest level, there are bacteria with just one cell type. And larger organisms have many more cell types. It is more or less impossible to get a precise count of the number of cell types in higher mammals. It is certainly several hundreds; for example, we have muscle cells, nerve cells, liver cells, etc. etc. There could be a number of forces acting behind an increase in the number of cell types. For example, with only one cell type, dessication would be a lot easier; so there would be a pressure to diversify into different cell types. Also, with more types of cell, obviously, an efficient distribution of duties can be made, which would be advantageous to the organism.

There is not much of a clear correlation between the genome size and advance in complexity. For example, chimpanzees and men have largely identical genomes, yet they are very different organisms in terms of complexity. Experts think that a few different genes make the most difference, rather than the total number of genes. They feel that it would therefore be useful to conduct studies of which genes are common, or "housekeeping genes", and which are distinct. And if there was a way to accurately measure the amount of useful DNA per cell of organisms, there should be a clear correlation with complexity. This field seems to be largely unexplored at the present time.

One of the most interesting things about complexity via increase in size is that body size is positively correlated with brain size; this is particularly true of the hominids, with an increase in body size showing an apparently clear increase in brain size. The logarithm of the brain size for animals of a diverse variety of species clusters roughly in a line with slope .75 if plotted against the logarithm of body weight. Having said that, there is no cut and dried relationship between brain size and behavioral complexity. The insects and the bees show remarkable memory and learning ability, although the brain size is very small. But, on the other hand, it is obvious to anybody that teaching, learning, and communication skills and methods are the most advanced among the higher mammals, the animals with the largest brain size.

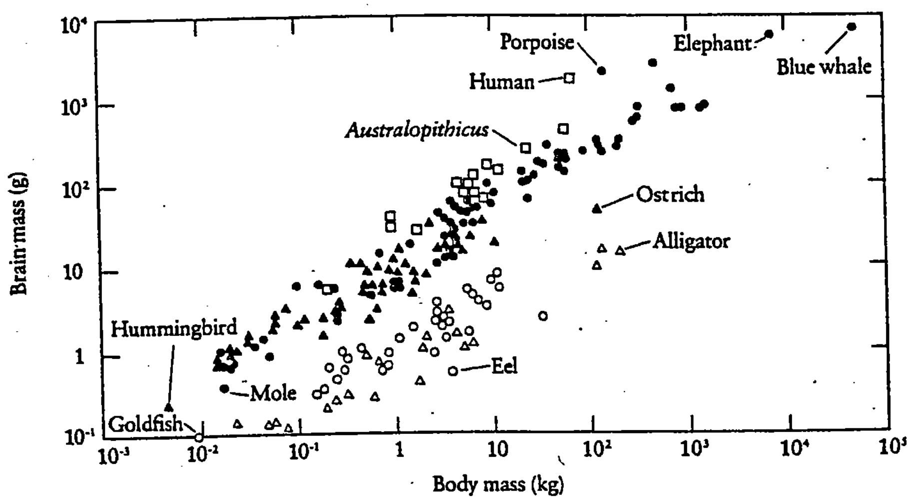
So it could be that as evolution progressed, there was a selection pressure on increase in complexity of one component, say cell types, and the others followed through. This is a plausible theory. Alternatively, selection pressures may act on all the components, although a change in one has an effect on the others. This is also a plausible theory.

Whatever be the actual process driving an extension in complexity, the experiment was successful on Earth. Complex life of a spectacularly diverse variety did emerge on Earth after single celled organisms came into being on the primitive Earth. But not all complex life forms show cleverness. Is there a selection for clever or intelligent behavior? We now come to discuss that final factor in the Drake equation: attainment of intelligence.

2.2.9. INTELLIGENCE

In discussing the emergence of intelligence, we have to first recognize that intelligence or apparently clever behavior varies in a continuum. Men are more intelligent than dolphins; dolphins are more intelligent than crocodiles; crocodiles are more intelligent than frogs; and so on. Second, the origin of human intelligence was marked by numerous chance events, and repetition of human intelligence under another set of biological and ecological parameters is generally believed to be extremely unlikely, bordering on the impossible. Third, there could be and indeed there is unconscious intelligence, apparently organized social activity driven by genetic evolution. And fourth, there may not be any selective advantage in acquiring intelligence; that is, attainment of intelligence may be the outcome of incidental random events, rather than a natural final outcome of life's evolution itself.

Thus, this is the least understood factor in the Drake equation, with the exception of longevity of advanced intelligence.



The brain size of 200 species of vertebrates plotted against their body size on a log-log graph. Primates are open squares; other mammals are solid dots, birds are solid triangles, bony fish are open circles, and reptiles are open triangles. (F[illegible] McMahon and Bonner 1983, Copyright © by *Scientific American Books*, redrawn from Jerison 1973.)

Regarding the development of intelligence, there is a divergence of opinion about its intrinsic likelihood; but on the other hand, there is a general agreement that there could be many different pathways to intelligence. For example, ants, turmites, spiders, etc. show signs of certain forms of technological capability and we may call this intelligence. Migratory birds follow Earth's magnetic lines in ways that humans do not understand. We may regard such behavior as intelligence. Dolphins are obviously capable of learning; they are regarded as being intelligent. Various primates are universally accepted to have intelligence. Yet these species are morphologically very different. Thus, it is conceivable that advanced intelligence need not be of the human type; other kinds of intelligence can develop that are capable of other types of intelligent activity.

As regards the intelligence of human beings, experts caution us about three things. First, it did not evolve in a linear way. Second, it was marked and influenced by numerous unpredictable chance events. Third, there is apparently no evolutionary advantage in acquiring intelligence. The usual example to make this argument is the example of bacteria, which have had extraordinary survival success without any intelligence. Thus whether advanced intelligence develops or not is probably a function of random events in the course of time. Evolutionary forces may select organisms that are better fitted under a set of circumstances, and the better fitted organism need not be a more complex organism. In the case of humans, the circumstances happened to be such that survival needed a multiple of very unusual developments, such as bipedalism, freeing of the forelimbs, ability of close visual examination with the hands, and the consequent increase in information stored in the brain. The morphological advances, namely bipedalism and use of forelimbs for other purposes, were very much the consequence of sudden climatic changes. Roughly 10 million years ago, with an uplift of magma from the Earth's interior, the land mass began to split away, and the equatorial forests started to disappear. This absolutely forced the monkeys to descend from the trees and live on land; walking upright and bipedalism was a consequence. Of all the continents in which the hominids could appear, in only one they did, in Africa. Many think that therefore it is hard to make the case that these advances which were seminal in the development of human intelligence were part of a natural process of life's evolution.

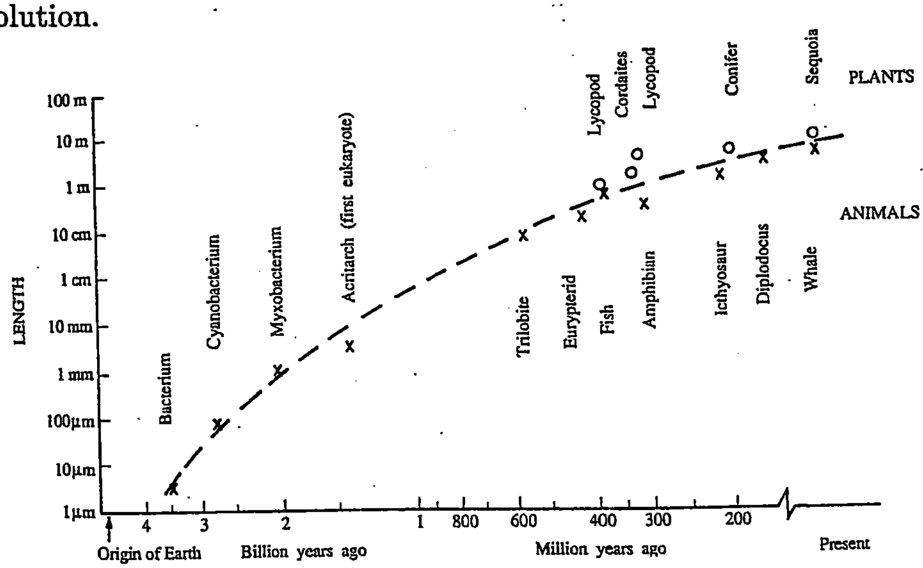


Fig. A graph showing a rough estimate of the maximum sizes of organisms at ... periods of life on earth. Note that both the length (or height) of the organisms and the time are on logarithmic scales. (Modified from Bonner 1965.)

Thus the jury seems to be still out on the likelihood of development of intelligence. Some are convinced that it is far from a natural final outcome of evolutionary processes. Others, while stating that exactly the same kind of intelligence would not occur twice, express the opinion that nature may invent intelligence in many ways. Geneticist H.J. Muller says, "... they (higher life forms) may be expected to follow radically different courses, ...,(but) would certainly be capable of achieving much mutual understanding with our own, since both had evolved to deal usefully with a world in which the same physico-chemical and biological principles operate." Evolutionists, to the contrary, have not expressed the optimism that advanced intelligence would naturally develop or that if it does, understanding each other would be at all possible.

We have now finished a discussion of the factors that enter into the Drake equation, except for the last factor, namely the longevity of advanced civilizations. So little is known about it, that we will discuss this factor only in the construction of the theoretical probabilistic model for the quantities in the Drake equation. We now proceed to that important aspect of this article.

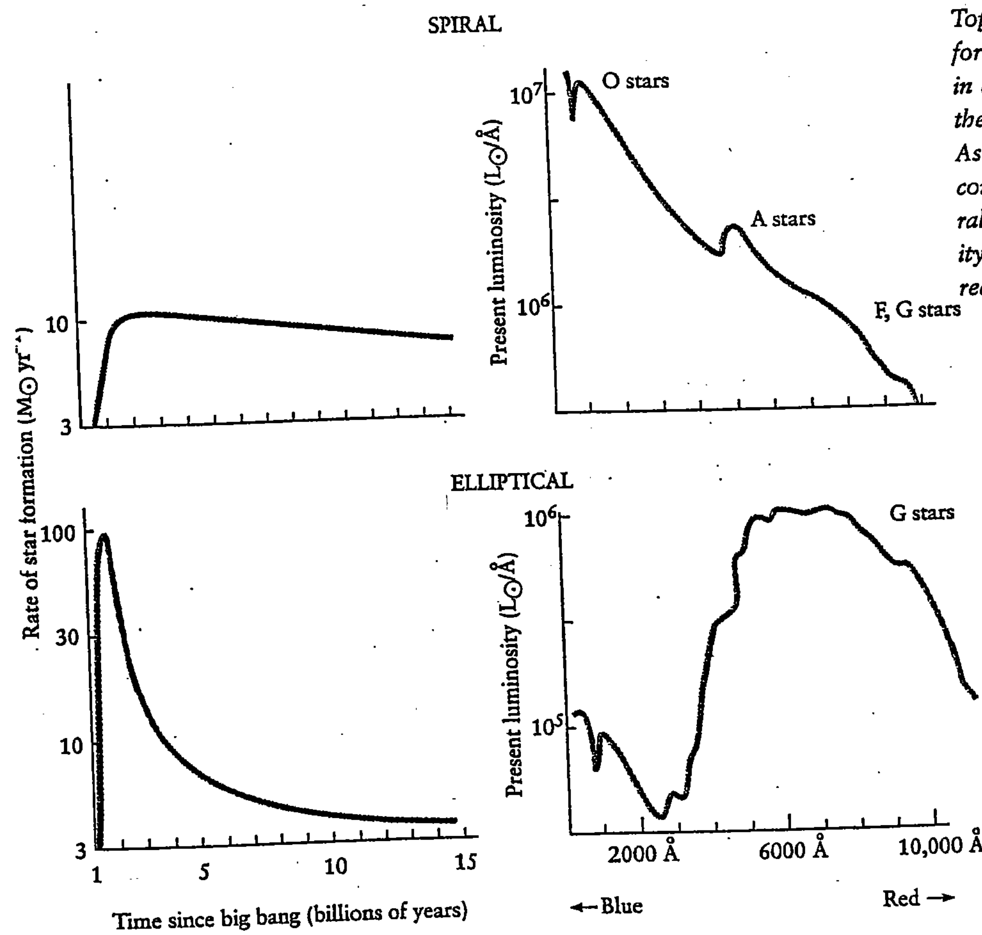
3. MODELLING THE FACTORS IN THE DRAKE EQUATION

3.1. STAR FORMATION RATE

This is the factor in the Drake equation about which we have the most information. Star formation in certain types of galaxies can happen in rare formation bursts separated by long time periods of inactivity. But that apparently is not the case for the Milky way galaxy (pp 206–211, Pagel (1997)). Thus, if T is the present age of the galaxy and S is the total number of stars at the present time, then a very naive approximation to $R = R(t)$, the star formation rate would be $R(t) = S/T$. We should note that the physics of star formation is very very complex, and R depends on many factors, such as mass of the gas present, pressure, temperature, effects of galactic rotation, chemical composition of the gas, and many additional factors; see pp 210 in Pagel (1997). There are no simple physical models (pp 209, Pagel (1997)).

In modelling R, we will take a probabilistic approach. We will model R as though the rate has been generally stable over time, with local fluctuations, which act like random errors. This error will be modeled here as a diffusion, more specifically an ORNSTEIN-

UHLENBECK PROCESS. In addition, for S and T themselves, we will assume certain probability distributions, as estimated values for S and T differ pretty widely from source to source. We will detail the probability distributions for S and T soon. First, we will describe the model for R.



Top: Stars in spiral galaxies continue to form at a steady rate, whereas most stars in elliptical galaxies formed early, when the galaxies were first created. Bottom: As a consequence, younger, bluer stars contribute most to the luminosity of spiral galxies, whereas most of the luminosity of elliptical galaxies comes from olde redder stars.

3.1.1. Modelling R(t) as a Stochastic Process

Let $B(t)$ denote the standard Brownian motion on $[0, \infty)$. Then the Ornstein-Uhlenbeck process $X(t)$ is defined as $X(t) = \exp(-t/2)B(\exp(t))$. We model $R(t)$ as

$$R(t) = S/T + X(t) \tag{3}$$

Note that even mathematically, the model cannot be exactly correct, because it leaves open the theoretical possibility that $R(t)$ could be less than zero. But S, T and the Ornstein-Uhlenbeck process $X(t)$ are such that the chance of $R(t) < 0$ according to model (3) is negligible. The reason for choosing the Ornstein-Uhlenbeck process for the random error part is that it is the only stationary Markov Gaussian process. If we do not wish the error to be stationary, even simple Brownian motion (perhaps scaled) would be a very reasonable model to try. The correlation structure of the Ornstein-Uhlenbeck process will be necessary for the mathematical calculations we will need to do. We will present that at the time of the calculations. A point of detail should be mentioned here; the error $X(t)$ is assumed to be independent of S and T.

3.1.2. Modelling S

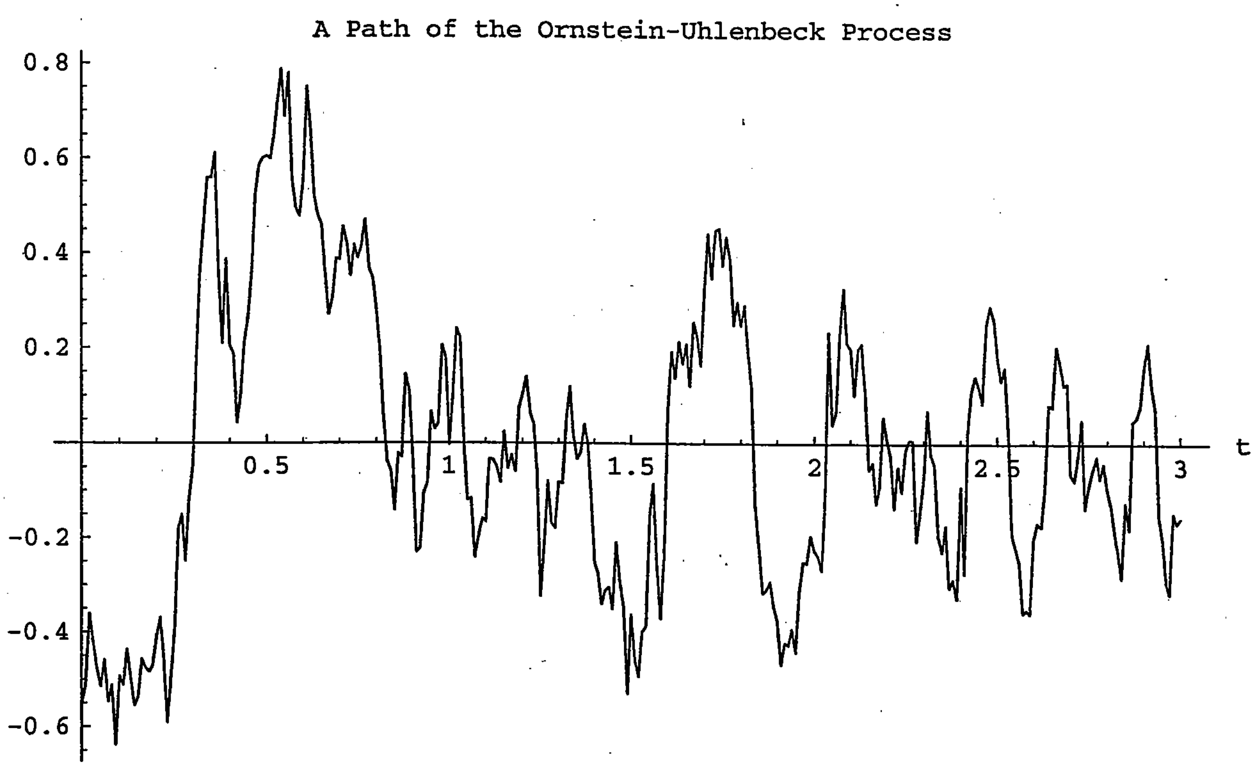
How many stars are there at the present time in the Milky way galaxy? Estimates given in different sources vary widely, between 100 and 400 billion stars. The discrepancy mostly comes from the assumption made about the mass of a typical star. Thus, one finds an estimate of the mass of the galaxy, and divides it by the mass of one star. Then one gets a ballpark figure for the total number of stars. Frequently one would see that the assumption is made that the mass of a typical star is one solar mass (our sun). This is an overestimate, and we wish to do this calculation somewhat more carefully.

Let M = mass of the galaxy, $M_{\cdot}$ the mass of the sun, M_c the mass of the interstellar dust and cloud, and M_{dm} the mass of the galactic dark matter. Let also w_{ij} be the mass of the ith star of spectral class j. Recall that there are seven spectral classes: O, A, B, F, G, K, M. Then,

$$M = M_c + M_{dm} + \sum[w_{ij}, \{j, 1, 7\}, \{i, 1, S_j\}] \tag{4}$$

where S_j is the number of stars of spectral type j.

Now, M_c is generally believed to be 5% of M. Everyone agrees that there should be substantial amounts of galactic dark matter; but the state of knowledge is poor. But there


A Path of the Ornstein-Uhlenbeck Process
0.8
0.6
0.4
0.2
-0.2
-0.4
-0.6
0.5
1
1.5
2
2.5
3
t

is reliable information about the percentages of stars of the different spectral classes, and how much a star of a spectral class weighs, on an average. Thus, from pp. 407 in Darling (2000):

Spectral Class	%	Average mass in solarmass
0	.0002	32
A	.09	6
B	.6	2
F	2.9	1.25
G	7.3	.9
K	15.1	.6
M	73.2	.2

Taking $M_c = .05M$, by ignoring the galactic dark matter, from equation (4), one has

$$.95M = S/100\ (32 * .00002 + 6 * .09 + 2 * .6 + 1.25 * 2.9 + .9 * 7.3 + .6 * 15.1 + .2 * 73.2)M.$$

$$\Rightarrow .95M = .36SM.$$
$$\Rightarrow S = 2.64M/M. \qquad (5)$$

Now, the ratio $M/M.$ in (5) can be found by applying *Kepler's third law:*

$$M/M. = \text{(Radius of orbit)}^3/\text{(Period of revolution)}^2 \qquad (6)$$

The sun makes one revolution around the galaxy in 200 to 250 million years (the number varies from source to source), and the radius of orbit is about 30,000 light years. Recalling that one light year = 63240 AU (we need to convert to AU in equation (5)), and taking the period of revolution as $200 * 10^6 * U$, where U is a Uniformly distributed random variable in [1,1.25], equation (5) will give:

$$S = 2.64M/M.$$
$$= 2.64(30000 * 63240)^3/(200 * 10^6 * U)^2$$
$$= 450.7 * 10^9/U^2. \qquad (7)$$

This is the probability model for S.

3.1.3. Modelling T

The present age of the Milky way is generally taken to be approximately the same as the age of the universe. Estimates for the age of the universe differ widely, and there is substantial controversy about various unresolved inconsistencies, such as a number of estimates of the age of the universe being less than the measured ages of the very old stars. Either those estimates for the age of the universe are incorrect, or the ages of the oldest stars are incorrect.

In the year 1929, astronomer Edwin Hubble made the startling discovery that distant galaxies are receding away from us, and noted that the further a galaxy is, the faster it is moving away. Denoting the recession velocity by v, and the distance of a galaxy by d, he wrote the linear equation

$$v = Hd \tag{8}$$

The constant H is now universally known as the *Hubble Constant.*

Now, if the speed of recession has been the same, and the age of the universe is T, then from equation (8) one will have $v = HvT \Rightarrow T = 1/H$. Thus, to a first approximation, the age of the universe is the reciprocal of the Hubble constant. This is a very very standard method to determine the time elapsed since Big Bang, although of course not the only one. We should mention here that it is NOT quite true that the speed of recession has been the same since Big Bang; and also that the relationship $T = 1/H$ is not correct if gravity is taken into account. Thus, truly, H is a function of time, although spatially a constant, from isotropic considerations of the universe. We will take T to be $1/H$.

The question now arises what is the current knowledge about the value of H? First we have to fix the unit. H is usually reported in the unit of kms. per megaparsec per second. Now 1 parsec is $3.125 * 10^{16}$ meters $= 3.125 * 10^{13}$ kms., and there are $60 * 60 * 24 * 365 =$ 31536000 seconds in a year. Thus, measured in years, from the *Hubble Law*:

$$\begin{aligned} T &= 3.125 * 10^{13} * 10^{6}/(31536000 * H) \\ &= 9.9093 * 10^{11}/H \end{aligned} \tag{9}$$

The measured value of H differs in a pretty wide interval, depending on the particular scheme used for measuring distances. Silk (1997, pp. 42 -44; also see pp. 32–35) describes the variation in the measurement of H as a function of different distance measurement methods. Silk reports that cosmologists believe H to be in the range 50 to 80, with a likely value of about 65 (in the unit km. per mpc. per second). More accurate determination of H has to await more and more accurate data. One can try to build a distribution for H by assigning more or less credibility on the different distance measurement methods. It will have a subjective element. For our purpose, we will assign to H a Beta distribution in the interval [50,80], with 65 as the expected value, and 65 ± 15 as the 3-σ interval around the mean value 65. If we take the Beta distribution to be a symmetric one around the mean value 65, then this results in the Beta density

$$f(H) = 7/1093500000(H-50)^3(80-H)^3, \ 50 \leq H \leq 80 \tag{10}$$

for H.

Thus, the probability model for T is

$$T = 990.93 * 10^9/H \tag{11}$$

where H has the Beta distribution in (10).

3.1.4. Modelling Proportion of Sun-like Stars

The proportion of stars that are sun-like should be regarded as a function of time. For emergence of life as in Earth, the parent star would have to be a relatively metal rich star. At the beginning, after the Big Bang, metals were not at all abundant in the universe. The metals came from supernova explosions and destructions of the first generation stars. Thus a sun-like star would have to be a second or later generation star. This would imply that for the first 2 billion years or so, the proportion of sun-like stars was negligible, or in fact zero.

The interpretation of what is a sun-like star depends on the specific problem one is interested in. For simple emergence of life, the constraints on the parent star, it seems, are much less than for emergence of an advanced intelligence, which on Earth required several billion years after the formation of the planet. These severe constraints on the parent star were discussed in section 2.2.1, and it was mentioned that there are about 1 billion stars that meet just the location and spectral class constraints. If we take a figure of 300 billion stars in the galaxy, this gives a proportion of only about .0033; that is, θ, the proportion of sun-like stars suitable for the emergence of an advanced civilization is very small. We adopt the somewhat optimistic uniform distribution in the interval [0,.01] for θ. This gives an expected value of about 1.5 times the .0033 figure given above. So we assume θ to be zero for $t < 2$, and a uniformly distributed random variable in [0,.01] for $t \geq 2$.

3.2. STARS WITH PLANETARY SYSTEMS

Planetary formation and discovery were discussed in section 2.2.2 and 2.2.3. More than 30 planets outside of our solar system have now been confirmed. So we know that planetary formation occurs elsewhere in the galaxy. But how common is planetary formation? The truth is that at the present state of knowledge, it is difficult to say anything accurately. Discovery of protoplanetary disks around a number of stars and confirmed detection of more than 30 planets have raised the hopes that planetary formation may be common. On the other hand, after examining many stars, planets have been detected in less than 10% (pp. 268, Ward and Brownlee (2000)) of the cases. However, the 10% figure must have a selection bias. The current methods to detect extrasolar planets can only determine large or very large planets. The most interesting planets, rocky planets, are not detectable using current methods. We assume a uniform distribution in the interval [0,.25] for the proportion of stars that have any planets, Earth-like or not.

3.3. HABITABLE PLANETS PER PLANETARY SYSTEM

The requirements of a planet to be habitable were discussed in section 2.2.4 and 2.2.5. We cannot state precisely what makes a planet habitable. But if we treat life on Earth as our model, the primary requirements are:

a. comfortable surface temperature over several billion years

b. the right size

c. location in the continuously habitable zone

d. plate tectonics

e. availability of liquid water over several billion years

f. developing and retaining a friendly atmosphere over several billion years

In addition, it has been often conjectured that there might be additional secondary factors in making a habitable planet, such as

g. presence of a massive planet to protect from destructive bombardment

h. a significant sized satellite such as our moon

i. a significant magnetic field

j. inclined equator to cause different seasons

At the time of the Green Bank conference in 1963, optimism was high that Earth-like planets would be abundant. In fact, the Green Bank meeting had estimated that there would be up to 5 habitable planets in each planetary system. Since then, the optimism, it seems, has muted. Many now hold the opinion that the number of habitable planets in a planetary system could frequently be zero, although one may see two or more occasionally. A Poisson distribution would seem a natural model for such a situation. If a habitable planet indeed must satisfy all or most of the properties $a - j$ above, then it is felt that at most about 1 in 10 systems may have such a planet. We will model n_e as having a Poisson(ε) distribution. Initially, ε will be taken to be .1. Note that for a Poisson distribution with mean .1, there is a 1 in 200 chance of there being 2 or more habitable planets per planetary system. Some might feel that this is optimistic. It might be. Only a sensitivity analysis will tell if another value of ε will make a radical difference in the final conclusions.

3.4. PROBABILITY OF EMERGENCE OF LIFE

As was discussed in section 2.2.6, the emergence of life on Earth remains such a mystery, that expert opinions on the likelihood of emergence of life under the right conditions vary from one extreme to the other. Biologists, impressed by the length of the highly complicated protein molecules, generally regard emergence of life as nearly impossible; on the other hand, astronomers, impressed by the quickness with which life arose on Earth as soon as it was environmentally possible, regard it as a natural outcome, perhaps requiring a catalytic substance that speeds up self organization and generation. We do know, however, that it is not impossible, as we know that it emerged on Earth.

We cannot ever rule out the possibility that life's emergence on Earth was a miraculous accident, or that it was a unique event designed by a creator. We cannot disprove such theories, but miracles and divine intervention, while matters of legitimate interest philosophically, are outside the domain of science. As a probabilist, my information is that whatever I know is about Earth, and that on Earth, it arose very quickly. Standard probability theory says that if in any trial a certain event may occur or not occur, and if it happens in a small number of trials, then the only conclusion allowed by a strict application of probability theory is that the event has a high likelihood of occurring in a single trial. It also amounts to saying that if a sufficiently large number of trials are conducted, the event would be observed to happen with a high probability. In our case, we quite do not have discrete trials, but a continuous time interval, and we want to know what is the probability that the particular event, namely emergence of life, would occur within a certain time interval. This calls for a bit of probabilistic modelling and a subsequent mathematical calculation.

Suppose that Z_1 is the time required for a habitable planet to form, and Z_2 is the time it takes for life to arise in a habitable planet. Let also L_p denote the time period for which a habitable planet remains conducive to existence of life. The factors that keep a planet conducive to life were discussed in section 2.2.4; for example, liquid water and a comfortable surface temperature are primary factors. From one Earth-like planet to another, Z_1, Z_2 and L_p would of course be different; we need to adopt probability distributions for them.

In the case of our solar system, the planets formed within a small window of time. But it is thought that the gas giants had to form quicker, as long as the gas was available (Taylor (1998)), and the terrestrial planets somewhat later, probably about 300 million years after the birth of the sun. It was also mentioned in section 2.2.6 that the evidence of the oldest life on Earth goes back to about 3.8 billion years ago. So if we take the age of the sun to be about 4.55 billion years, then the time taken for life to arise after the formation of Earth is about $4.55 - .3 - 3.8 = .45$ (billion years). We may think of Z_1 and Z_2 to be random variables with expected values .3 and .5, respectively. What about L_p?

Our Earth has existed for about 4.3 billion years, and the sun was born about 4.55 billion years ago. We mentioned in section 2 that the sun has a residual life of another 5 to 5.5 billion years. However, the effective residual life of Earth is much less. In another 500 million years to 3 billion years, the sun would get extremely bright, causing totally catastrophic consequences to Earth. It will start with vaporization of our oceans, and the slow death of all life. It is severely unlikely that Earth can sustain any life for more than another 1 to 3 billion years.

Thus if we take Earth as a model, L_p should be roughly within the range 5.5 to 7.5 (billion years). But we still have to adopt a probability distribution within this range.

An interesting property of the Exponential distribution is that for a specified value of the mean, it maximizes the ENTROPY among positive random variables (Kagan,Linnik and Rao (1973)); on the other hand, on a bounded range $[a, b]$, entropy is maximized by the uniform distribution in that range. Entropy is a widely accepted measure of uncertainty. So with the limited amount of knowledge we have about Z_1, Z_2, and L_p, all our knowledge being only about our Earth, it seems not unreasonable to assume that Z_1 is Exponentially distributed with mean .3, Z_2 exponentially distributed with mean .5, and L_p uniformly distributed on [5.5, 7.5]. Life would be observed on our generic habitable planet if and only if $Z_1 + Z_2$ is smaller than L_p. Thus, we want to find $P(Z_1 + Z_2 \leq L_p)$. We will assume in this calculation that the three random variables are independent.

In the next section, a mathematical formula for this probability is stated for general Exponentially distributed random variables Z_1, Z_2 and a general uniformly distributed random variable in an interval $[a, b]$. If the means of the two exponentials are .3 and .5, and if $a = 5.5$ and $b = 7.5$, then that formula gives a numerical answer of .9999. It is interesting that a formal probability calculation using Earth data as our information, we get an answer that vindicates the physicists' view that life should naturally form, when the conditions are right. It seems silly to adopt .9999 as the probability of emergence of life in the Drake equation; we will simply take it to be 1.

3.5. PROBABILITY THAT LIFE EVOLVES TO COMPLEXITY

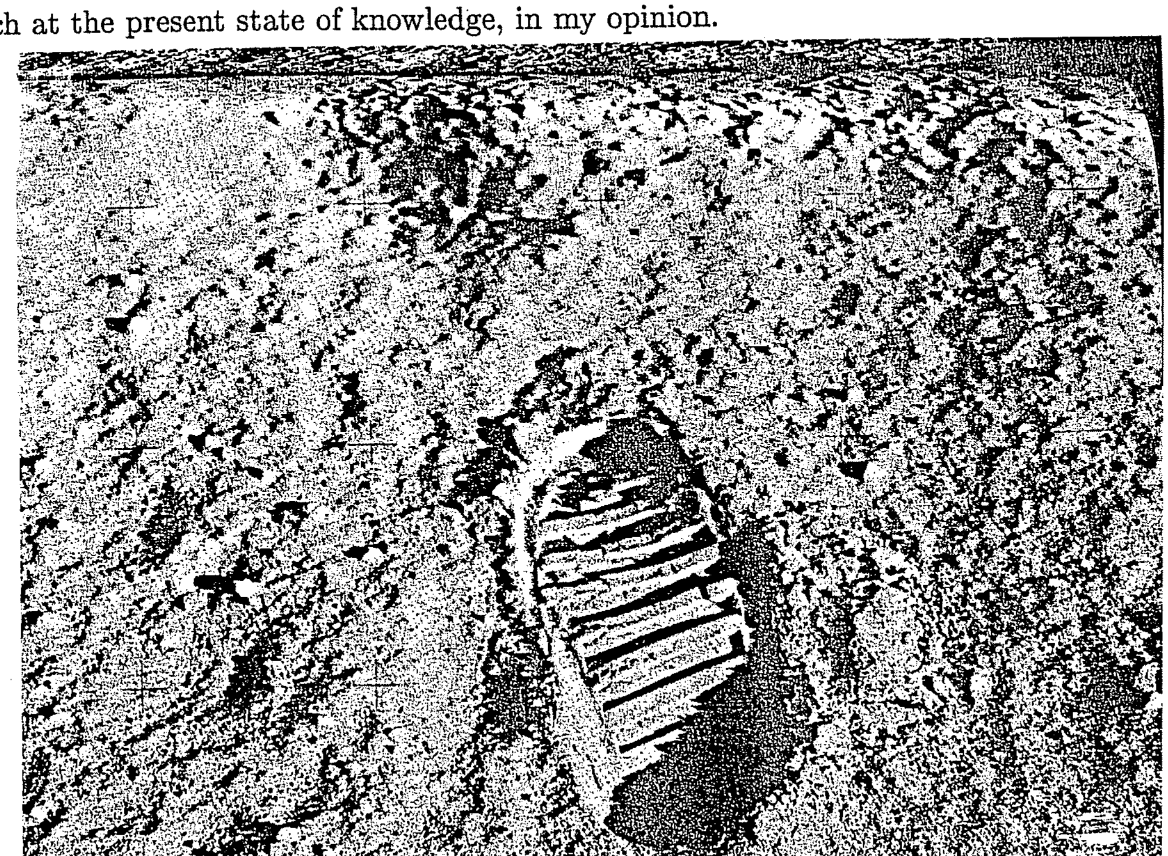
Now we come to the next factor in the Drake equation, namely that life, if it arises, advances to complexity. We cannot define complexity precisely. We can take the view that complexity is a state of existence that takes a certain amount of time (perhaps a large amount of time). The question then is whether adequate time would be available for such an evolution to take place, within the effective healthy life of a habitable planet. If then we denote Z_3 to be the time needed for life to evolve to a state we call complexity, what we want is the conditional probability that $Z_1 + Z_2 + Z_3 \leq L_p$ given that $Z_1 + Z_2 \leq L_p$.

Now, how long did it take for life to advance to complexity on Earth, the only planet we know something about. As we said before, the answer depends on what exactly we mean by complexity. In section 2.2.8, we discussed the manifestation of complexity, by increase in size, or an increase in number of cell types, or an increase in the amount of useful DNA. We seem to have little information on genomic complexity, and so perhaps we can enquire about the time it took for an increase in cell types or a "visible" size increase in organisms on Earth. Multicellular algae and seaweeds are firmly believed to have existed about 1 billion years ago (Ward and Brownlee (2000), Jakosky (1998)). By about 800 million years ago, organisms measuring 1 cm are thought to have existed (Bonner (1988), pp 27). The invention of sex was accomplished about 1 billion years ago. Thus, in a variety of ways, unambiguous complexity, in size, shape, and reproductive behavior, were attained 1 billion years ago. Since life arose about 3.8 billion years ago, this would place the time taken to achieve complexity at the doorstep of about 3 billion years. We may adopt Z_3 to be Exponentially distributed with mean 3. Notice that if we take Earth as our model, of all the stages of advancement, attainment of complexity seems to take the longest amount of time.

Again, in section 4 a general formula is provided for the conditional probability $P(Z_1 + Z_2 + Z_3 \leq L_p | Z_1 + Z_2 \leq L_p)$. Substituting into this formula the means .3,.5, and 3, and 5.5 and 7.5 for a and b, we will get a numerical answer of .85. Instead of taking the fixed .85 value, taking the path of caution, we will treat f_c to be uniformly distributed in the range [.7,1], giving f_c an expected value of .85. The implication of using a probability distribution for f_c instead of a fixed value is that as we do repeated simulations of the Drake equation, different values of f_c within the range [.7,1] will occur in the simulations. This will protect against the subjective use of one fixed value for f_c, which seems unwise in a problem infected with lack of much information.

3.6. PROBABILITY OF EMERGENCE OF INTELLIGENCE AND CIVILIZATION

A calculation such as in section 3.5 above for these two probabilities by using Earth data would be much harder to justify. The reason is that there is too much skepticism about the hypothesis that intelligence and civilization are assured outcomes of evolution if only sufficient time would be available. In contrast, many really believe firmly that emergence of intelligence and/or civilization would be dependent on random environmental events, and indeed there is no evidence that acquiring intelligence has a selection advantage. Consequently, we have very little justification to calculate f_i and f_a in the Drake equation as in section 3.5, because that calculation in essence is built on the premise that life and complexity would attain as outcomes of natural processes and of evolution if infinite time was available, and the question really is if they would arise within a finite time, namely the effective lifetime of a planet. We are saying that premise is probably invalid when it comes to intelligence and civilization. It seems rational, however, to expect that building an advanced civilization would be harder than acquiring only intelligence. It seems that making any more assumptions about f_i and f_a would be factually unwarranted. So to honestly reflect this lack of understanding, we will use a uniform distribution on [0,1] for f_i and a uniform distribution on [0,.5] for f_a. Particular groups of experts may feel these are too optimistic; but it does not seem right to adopt a distribution that would reflect a greater amount of confidence in our understanding and knowledge about f_i or f_a. Again, in the repeated simulations of the Drake equation that we will actually do, in section 5, different values of f_i and f_a would thus be used in the different simulations, and that is the correct approach at the present state of knowledge, in my opinion.



re Man's footprint on the Moon. Closeup of one of the footprints left by Apollo–11 astronauts Neil Armstrong or Edwin Aldrin on the surface of the Moon during their historic visit, 20–21 July 1969.

3.7. LONGEVITY OF ADVANCED CIVILIZATIONS

In the very original version of the Drake equation, the quantity L was taken to be the time during which an advanced civilization remains detectable. The exact definition of L would depend on the purpose of a project. The purpose of SETI was primarily detection and/or contact with an advanced civilization. But in the article here, we are primarily interested in the greater intellectual question of existence, regardless of whether we can detect or contact. So for us, the appropriate meaning of L is the longevity of an advanced civilization.

Estimates of factors in the Drake Equation for communicative civilizations

Author	Date	R^*	f_p	n_e	f_l	f_i	f_c	L	N
Green Bank	1963	1–10	.5	1–5	1	1	.1	10^3–10^8	$< 10^3$–10^9
Cameron	1963		1	.3	1	1	.5	10^6	2×10^6
Sagan	1963	10	1	1	1	.1	.1	10^7	10^6
Shklovskii/ Sagan	1966	10	1	1	1	.1	.1	10^7	10^6
Byurakan	1971	10	1	1	———	.01	———	10^7	10^6
Oliver	1971	20	.5	1	.2	1	.5	?	$= L$
Rood/ Trefil	1981	.05	.1	.05	.01	.5	.5	10^4	.003

R^* = rate of star formation, f_p = fraction of stars forming planets, n_e = number of planets per star with environments suitable for life, f_l = fraction of suitable planets on which life develops, f_i = fraction of life-bearing planets on which intelligence evolves, f_c = fraction of intelligent cultures communicative over interstellar distances, L = lifetime of a communicative civilization, N = number of communicative civilizations in the Galaxy at a given time.

Now, what do we know about possible longevity of an advanced civilization? Very little factually; we do have some understanding of what affects L, however. For example, it is thought that the human civilization on Earth can get extinct in any of the following ways:

a. a disease such as AIDS which is transmitted more easily than AIDS;

b. uncontrollable disaster from genetic engineering and gene therapy;

c. nearby supernova;

d. nearby gamma ray burst;

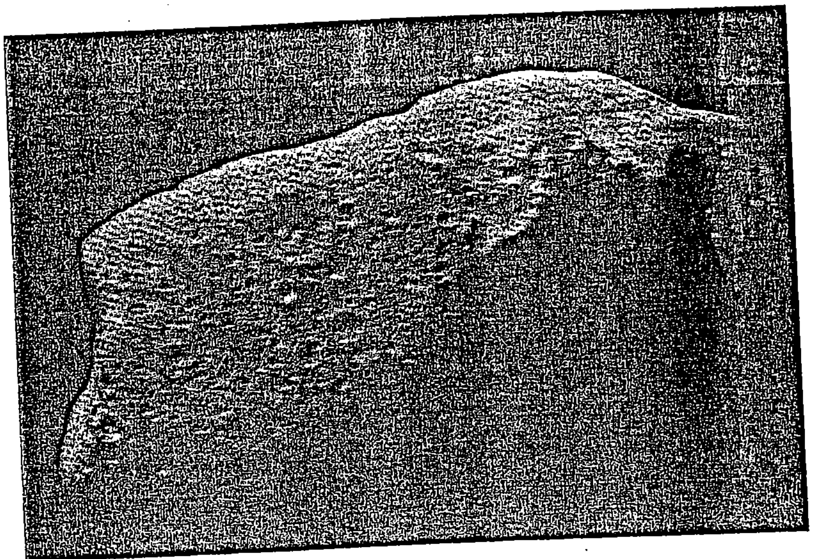
e. collision with Earth-crossing asteroid or comet;

f. climate change, and especially temperature;

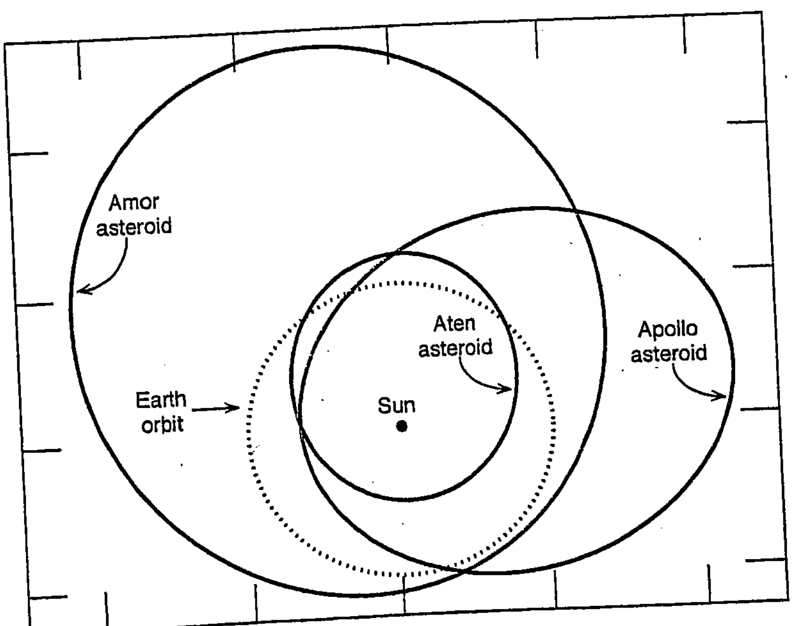
g. slow decrease in fertility;

h. nuclear war.

We can only speculate about emergence of easily transmitted viruses, and consequences of genetic experimentation. About the other factors, we have some information. Supernovae are not that rare within the galaxy: more than one occurs in a century (pp. 527, Allen's Astrophysical Quantities (2000)); one within a thousand light years of Earth would be fatal to life on Earth. The gamma ray bursts, so far, appear to be all extragalactic; but their cause is not known, and we cannot say whether one in our vicinity is likely and in what time period. But if one were to occur, it would apparently sterilize the planet. Earth crossing asteroids pose a much greater danger. Many earth crossing asteroids are already known, and astronomers think that in only as little as 10,000 years a sizeable asteroid could hit Earth. Scientists probably have the technological capability to deflect or substantially destroy one such asteroid shortly before impact, but a real danger is that detection could be difficult. If an impending colliding asteroid happens to be in or near the same plane, then we may have only a day before we know that an impact is going to occur. Actually, a lot of scientists think that we are grossly underprepared in our research on protection against asteroidal impacts. Greenhouse warming and climate change have been topics of concern for more than a decade. There has been an increase in Earth's surface temperature in the last 100 years. But it is hard to tell if there is a trend. But the

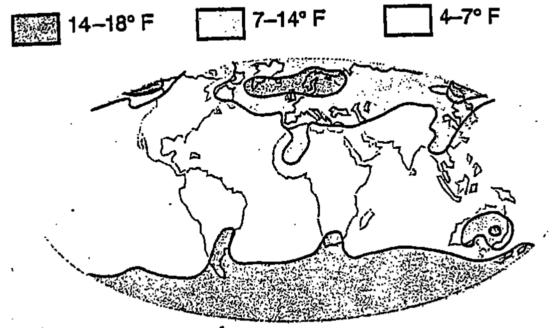


Ida, a typical asteroid, 56 kilometres long. It has had a long history of collisions shown by its pock-marked face (NASA).

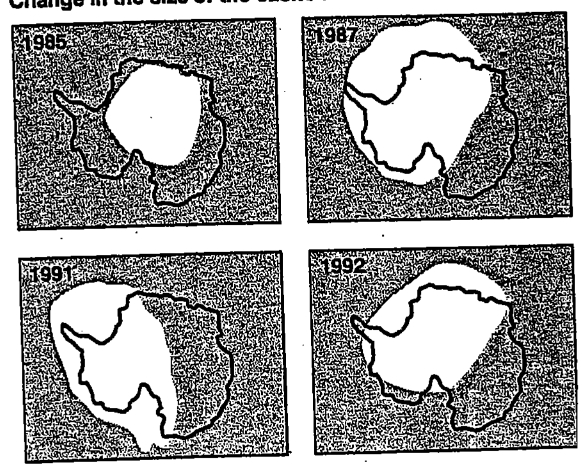


Typical orbits of the Apollo, Aten and Amor Near-Earth asteroids.

Possible rises in temperature by 2050



Change in the size of the ozone hole over Antarctica



signs are worrisome. Large icebergs have broken up very recently. Sea life in the waters at the Aleutian islands in Alaska have gotten destroyed in a very very short time span. Temperature increase is a cause of justified concern. Similar concern exists and has started to attract international attention, about spread of biological and nuclear weapons. With the wide advancement in access to the internet, and our inability to control its content, utterly deadly weapons may become readily available or it may be possible to put them together easily in a short amount of time. It seems to be a very viable route to large scale destruction. State sponsored wars, at our present state of weapon technology, also can cause total extinction. Human beings have a moral burden to intercept these possibilities. And finally, as just a natural process, presumably the human species may get extinct being unable to cope with changing environments. In fact, statistics are not favorable to us if we extrapolate from other species. The more complex species, generally, get extinct faster, and we are the most complex of all species. Depending on our own behavior, and luck, the human species could get destroyed quickly, or it may survive for a long time. It has been suggested that the next 100 years would be crucial in determining our fate.

To describe our probability distribution for L, we first need some more notation. In addition to Z_1, Z_2, and Z_3 introduced before, let Z_4 denote the time taken for complexity to advance to intelligence, and Z_5 the time taken for an intelligent species to develop a civilization. Z_4 and Z_5 are a formal necessity in this development of the distribution for L; we do not wish to suggest that we are now saying that intelligence and civilization arise as part of the natural process. In the case of Earth, the mammals started to truly flourish about 65 million years ago, with the demise of the dinosaurs. If we interpret intelligence very loosely, and assign intelligence to some of those mammals, then it took about 935 million years after the emergence of complexity for intelligent life to arise. And the only civilization, namely the human civilization, started four or five thousand years before the birth of Christ, with the construction of the Pyramids and the sumerian city of Ur. In the geological time scale, this is basically time zero from present. We may round Z_4 and Z_5 in the case of Earth to 1 and .1 (billion years).

Now, the longevity L of any civilization is constrained by:

$$Z_1 + ... + Z_5 + L \leq L_p, \tag{12}$$

where L_p is the effective lifetime of the planet itself. This is a physical constraint.

But otherwise, the longevity L could be quite small, just a few thousand years, or indeed very large! We just do not know. In such a situation, probabilists frequently use the Cauchy distribution as a model, which has a reputable heavy tail. Since we obviously have a positive random variable to model, we may consider the absolute value of a Cauchy as a model, and scale it in a way that say the median is a number that experts feel is a likely value for L. Experts seem to feel that L might be something like 10,000 years. If we use the absolute value of a Cauchy distribution with a scale parameter $\sigma = 10^{(-5)}$, then the median is $10^{(-5)}$ (billion years), which is 10,000 years. By adding on the constraint from 12, we model L as follows:

$$L \sim \max[0, \min\{|\text{Cauchy}(0, \sigma)|, L_p - Z_1 - \ldots - Z_5\}], \tag{13}$$

where $Z_1, \ldots, Z_5$ have Exponential distributions with means .3,.5,3, 1, and .1 respectively. They and L_p are taken to be independent.

This finishes our description of the probability model for the factors in the Drake equation. To simulate this model, however, first we need some supporting mathematical calculations. In the next section, we state these results, but do not prove them. The proofs are postponed till the appendix in section 8.

4. SOME ANALYTICAL RESULTS

First we will assemble the full model and all the notation for future reference.

The unit of time is billion years. A generic time would be denoted as t. First the notation:

$R(t) =$ Star formation rate at time t in the galaxy

$\theta(t) =$ proportion of stars born at time t that are sun-like

$S_s(t) = \theta(t) * R(t)$

$S_p(t) =$ # stars among sun-like stars born at time t that acquire a planetary system

$n_e =$ # habitable planets per planetary system

$$P_h(t) = \sum_{i=1}^{S_p(t)} n_{e,i}$$

= # habitable planets around sun-like stars born at time t having a planetary system

$P_l(t) =$ # planets among the $P_h(t)$ in which life would arise

$P_c(t) =$ # planets among the $P_l(t)$ where life would evolve to complexity

$p_{ex} = P$(an extinction event destroys all complex life on a habitable planet)

(the value of p_{ex} would be discussed in section 5 when we report the simulation)

$P_s(t) =$ # planets among $P_c(t)$ where complex life sustains through all extinction events

$P_i(t) =$ # planets among the $P_s(t)$ where complex life would advance to intelligence

$P_a(t) =$ # planets among $P_i(t)$ where intelligence would advance to a civilization

$\theta_p = P$(a sun-like star acquires a planetary system)

$f_l = P$(life would arise in a habitable planet)

$f_c = P$(life evolves to complexity once it arises)

$f_i = P$(complex life advances to intelligence)

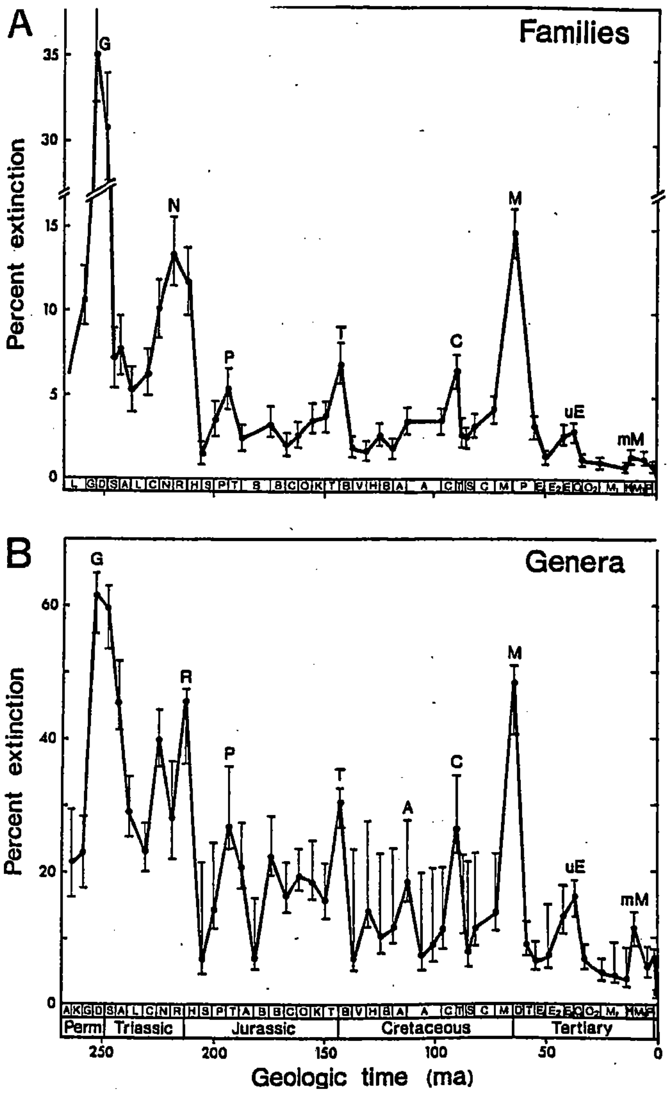
$f_a = P$(intelligent life acquires a civilization)

$Z_1 =$ time taken for a habitable planet to form

$Z_2 =$ time taken for life to arise in a habitable planet

$Z_3 =$ time taken for life to evolve to complexity

Extinction Events on Earth



Picture [illegible] by the Hubble Space Telescope of the fading glow *(arrow)* of an enigmatic gamma ray burst detected hours before by NASA's Compton Gamma Ray Observatory in orbit around Earth.

Z_4 = time taken for complex life to advance to intelligence

Z_5 = time taken for intelligent life to acquire a civilization

L_p = Effective time during which a planet stays habitable

L = longevity of a civilization

T = present age of the galaxy

N_a = # civilizations in the galaxy at the present time

We assume:

a. $S_p(t)|S_s(t), \theta_p \sim \text{Bin}(S_s(t), \theta_p)$

b. $P_l(t)|P_h(t) \sim \text{Bin}(P_h(t), f_l)$

c. $P_c(t)|P_l(t), f_c \sim \text{Bin}(P_l(t), f_c)$

d. Extinction events form a homogeneous Poisson point process; the rate of this Poisson process would be discussed in the section where the actual simulation is presented

e. $N_e = \#$ extinction events experienced by complex life on a planet

f. $P_s(t)|P_c(t), N_e \sim \text{Bin}(P_c(t), (1 - p_e x)_e^N)$

g. $P_i(t)|P_s(t), f_i \sim \text{Bin}(P_s(t), f_i)$

h. $P_a(t)|P_i(t), f_a \sim \text{Bin}(P_i(t), f_a)$

Recall that the quantities involved in $S_s(t) = R(t) * \theta(t)$ were already modeled in section 3. One comment is in order here: in consideration of the extinction events, we have adopted the view that although extinction events happen consistently through time, noncomplex life does not get totally extinct by them (perhaps they can survive in deep sea, etc.). We are also going to adopt the position that once intelligence is established, a way to avoid complete extinction from an extinction event would be figured out. Thus, in our way of accommodating the extinction events, only those that occur after complexity has been attained but before intelligence has been established would count. This time window, note, has been denoted as Z_4 in the above.

Also recall that we are assuming:

i. $f_p \sim U[0, .25]$

j. $f_l = 1$

k. $f_c \sim U[.7, 1]$

l. $f_i \sim U[0, 1]$

m. $f_a \sim U[0, .5]$

The following results are needed in the rest of the aricle, which we state without a proof.

Result 1.

Let $m = 1.47875 * 10^6$, and $v = 1.75001 * 10^{12}$.

Then, $P_h(t)$ is approximately distributed as $N(m, v)$, that is, normal with mean m and variance v.

Result 2.

Let Z_1, Z_2, L_p be independent random variables, with $Z_1 \sim \exp(\lambda_1)$, $Z_2 \sim \exp(\lambda_2)$, and $L_p \sim U[a, b]$. Then,

$$P(Z_1 + Z_2 \leq L_p) = 1 - \frac{\mu_2^2(e^{-\frac{a}{\mu_2}} - e^{-\frac{b}{\mu_2}}) - \mu_1^2(e^{-\frac{a}{\mu_1}} - e^{-\frac{b}{\mu_1}})}{(b-a)(\mu_2 - \mu_1)} \tag{14}$$

Result 3.

Let Z_1, Z_2, Z_3, L_p be independent random variables, with $Z_1 \sim \exp(\lambda_1), Z_2 \sim \exp(\lambda_2)$, $Z_3 \sim \exp(\lambda_3)$, and $L_p \sim U[a, b]$. Then,

$$P(Z_1 + Z_2 + Z_3 <= L_p)$$
$$= 1 - \frac{\mu_1^3(\mu_3 - \mu_2)(e^{-\frac{a}{\mu_1}} - e^{-\frac{b}{\mu_1}}) - \mu_2^3(\mu_3 - \mu_1)(e^{-\frac{a}{\mu_2}} - e^{-\frac{b}{\mu_2}}) + \mu_3^3(\mu_2 - \mu_1)(e^{-\frac{a}{\mu_3}} - e^{-\frac{b}{\mu_3}})}{(b-a)(\mu_2 - \mu_1)(\mu_3 - \mu_2)(\mu_3 - \mu_1)} \tag{15}$$

Result 4.

Let $t_U = T - Z_1 - Z_2 - \ldots - Z_5$, and $t_L = t_U - L$. Then N_a, the number of civilizations existing in the galaxy at the present time equals the stochastic integral

$$N_a = \int_{t_L}^{t_U} P_a(t)dt \tag{16}$$

5. SIMULATION OF THE THEORETICAL MODEL

In this section we will present a simulation of the theoretical model presented above. The simulation will proceed up to obtaining N_a. In the next section, the values of N_a simulated here will be plugged into a spatial compound Poisson process model for the distribution of the civilizations in the galaxy. That analysis will result, through some more mathematical results, in the distance to the nearest such civilization. Below we describe the steps used in the simulation here; the simulation size is 500, i.e., the theoretical model presented above was simulated 500 different times.

Before laying out the steps of the simulation, we will discuss the rate of extinction events and the likelihood of destruction of all complex life in any extinction event. First, half a dozen or more mass extinction events in the history of the Earth are well documented. In the Triassic event, as much as 90% of all species alive got extinct; in the K/T event about 65 million years ago, the dinosaurs and as much as 50% of all species got extinct. Several theories have been suggested to explain these extinction events. One of them is a periodic reappearance of a star every 26 million years, causing a gravitational stream of cometary impacts with Earth. The periodicity theory is doubted by many scientists. We will not enter into the debate about the validity of the periodicity theory; if true, periodic extinction events would be very regular. We prefer to model extinction events occurring according to a Poisson point process, with a mean (rate) of 25 million years. This converts to a rate of 40 for our Poisson process in the billion year unit. Also, as we mentioned before, concurring with Ward and Brownlee (2000), we will count only those extinction events that occur after the emergence of complexity but before the origin of intelligence. Thus, according to the Poisson process specification, the number of extinction events to be accounted for would have a Poisson $(40 * Z_4)$ distribution, given Z_4, the time period between origin of complexity and intelligence.

As regards p_{ex}, the probability of destruction of all complex life in any extinction event, we have no objective information. It seems that p_{ex} should be small. How small? I must admit we do not know. I have taken p_{ex} to be 1 in 1 million, i.e., $p_{ex} = 10^{(-6)}$. We are now ready to outline the steps of the simulation.

Step 1. Simulate H (the Hubble constant) as $50 + 30 *$ Beta $(4, 4)$;

Step 2. Obtain T as $990.93 * 10^9/H$;

Step 3. Simulate $Z_1, \ldots, Z_5$ according to their Exponential distributions;

Step 4. Simulate L_p according to the $U[5.5, 7.5]$ distribution;

Step 5. Simulate L according to the rule in equation (13);

Step 6. Obtain t_U and t_L as defined in Result 4 above;

Step 7. To approximate the integral in equation (16) for N_a by an average, obtain the values in the discrete grid

$$t(i) = t_L + iL/20, i = 0, 1, ..., 20;$$

Step 8. By using Result 1, simulate $P_h(t)$ at values of t in the above discrete grid;

Step 9. Set $P_l(t) = P_h(t)$ as f_l is taken as 1;

Step 10. Simulate f_c according to the $U[.7, 1]$ distribution;

Step 11. Simulate $P_c(t)$ as $\text{Bin}(P_l(t),\ f_c)$;

Step 12. Simulate N_e, the number of extinction events as Poisson $(40 * Z_4)$;

Step 13. Simulate $P_s(t)$ as $\text{Bin}(P_c(t),\ (1 - p_{ex})^{N_e})$;

Step 14. Simulate f_i according to the $U[0, 1]$ distribution;

Step 15. Simulate $P_i(t)$ as Bin $(P_s(t), f_i)$;

Step 16. Simulate f_a according to the $U[0, .5]$ distribution;

Step 17. Simulate $P_a(t)$ as Bin $(P_i(t), f_a)$;

Step 18. Obtain N_a as $L/21 \sum_{i=0}^{20} P_a(t(i))$

The main results of the simulation are now reported.

Mean of N_a over the 500 simulations: 6.88

Median of N_a : 0

simulations in which N_a was obtained to be zero: 262

Standard deviation of $N_a = 52.11$

Quartiles of N_a: 0,0,2

Maximum value of N_a over the simulations: 904

$P(N_a = 0) = 262/500 = .524$

$P(N_a \leq 1) = .696$

$P(N_a \leq 2) = .782$

$P(N_a \leq 3) = .842$

$P(N_a \leq 5) = .878$

$P(N_a \leq 10) = .932$

$P(N_a \leq 15) = .956$

$P(N_a \leq 75) = .988$

The conclusion from these 500 simulations of our theoretical model is that advanced civilizations that would take many billions of years to arise on quite special planets around rather special stars and have to sustain, initially, through extinction events are sparse in the galaxy. In fact, in more than 50% of the simulations, there are supposed to be no civilizations present at this time at all. We MUST remember, however, that if we seriously mistrust the theoretical model, then automatically we must discard the simulations as well. In the final analysis, that judgement has to be the user's, in such a difficult problem with limited actual information. We might recall, however, that several factors in the Drake equation were in fact modeled optimistically by us; for example, f_l, the probability of emergence of life, was taken to be 1. So no deliberate attempts to construct a pessimistic model were made. But still, a sensitivity analysis would be useful.

6. DISTANCE TO THE NEAREST CIVILIZATION

An interesting question, from the perspective of SETI, as well as intellectually, is the distance of Earth to the nearest civilization. The simulations of section 5 will be used in conjunction with a model for spatial distribution of civilizations in space to give an estimate for this nearest distance. We will in fact obtain estimates of two distances; one for the distance to the nearest civilization given that there is one within Milky way, and the other is an unconditional distance to the nearest one. The latter estimate would have to be treated with greater skepticism because it will implicitly extrapolate our theoretical model based on Milky way data into the universe. Still, it seems it would be somewhat interesting to have an estimate of the unconditional distance as well. Quite a bit of mathematical derivations are in fact necessary to arrive at estimates of these distances. But, as in section 5, only the formulae will be given here, and the actual derivation will be deferred till section 8, the appendix.

Model for Spatial Distribution of Civilizations

Poisson processes are standard counting process models for distribution of events in space. To impart some additional flexibility, we will model civilizations in space to be distributed as a COMPOUND POISSON PROCESS, i.e., conditional on λ, it is a stationary Poisson process with rate λ, and λ has a distribution G. For specificity, we take G to be a Gamma(α, β) distribution, with the parameters α, $\beta > 0$. The parameters α and β would not be assumed known; they will be estimated from the results of the simulations in section 5.

The results below give formulae for the expected distance to the civilization nearest to Earth based on the compound Poisson process model; a conditional expected distance given that there is at least one civilization in Milky way, as well as an unconditional expected distance are given. The distance to the nearest civilization is denoted as '*d*' in the two following results.

Result 5.

Under the above compound Poisson process model, the expected distance to the nearest civilization given that at least one exists within Milky way equals

$$E(d|N_a \geq 1) = \text{The expression in equation (33) in the appendix.} \tag{17}$$

Result 6.

The expected distance to the nearest civilization in the universe equals

$$E(d) = \int_0^\infty \frac{1}{(1+\frac{4}{3}\pi r^3\beta)^\alpha} dr \text{ if } \alpha > 1/3$$
$$= \infty, \text{ if } \alpha \leq 1/3. \tag{18}$$

The two expected distance formulas (17) and (18) involve the parameters α and β. They would be estimated from the simulations of section 5 by using the following result.

Result 7.

Under the above compound Poisson process model,

$$P(N_a = 0) = 3^\alpha/(3 + 500\pi\beta)^\alpha = \eta \text{ (say)} \tag{19}$$

$$E(N_a) = 500\pi\alpha\beta/3 \tag{20}$$

REMARK. In (19) and (20), the number 500 comes as an output of the fact that the diameter of Milky way is 100,000 light years. The derivation will be seen in the appendix.

Combining (17),(18),(19) and (20) with the simulations of section 5 one obtains an estimated expected distance to the nearest civilization, conditional as well as unconditional. The steps are explained below.

Recall from section 5 that the simulations give $P(N_a = 0) = .524$ and $E(N_a) = 6.88$. Thus, the parameters α and β are estimated by solving the equations

$$500\pi\alpha\beta/3 = 6.88$$
$$\text{and } 3^\alpha/(3 + 500\pi\beta)^\alpha = .524 \tag{21}$$

The solutions are:

$$\alpha = .17476, \beta = .07519 \tag{22}$$

Substituting these values into (17) and (18) gives:

I. The estimated expected distance to the nearest civilization if at least one exists within Milky way is 25,594.4 light years;

II. The unconditional estimated expected distance to the nearest civilization is infinite (because the estimated value of alpha is .17, which is less than 1/3).

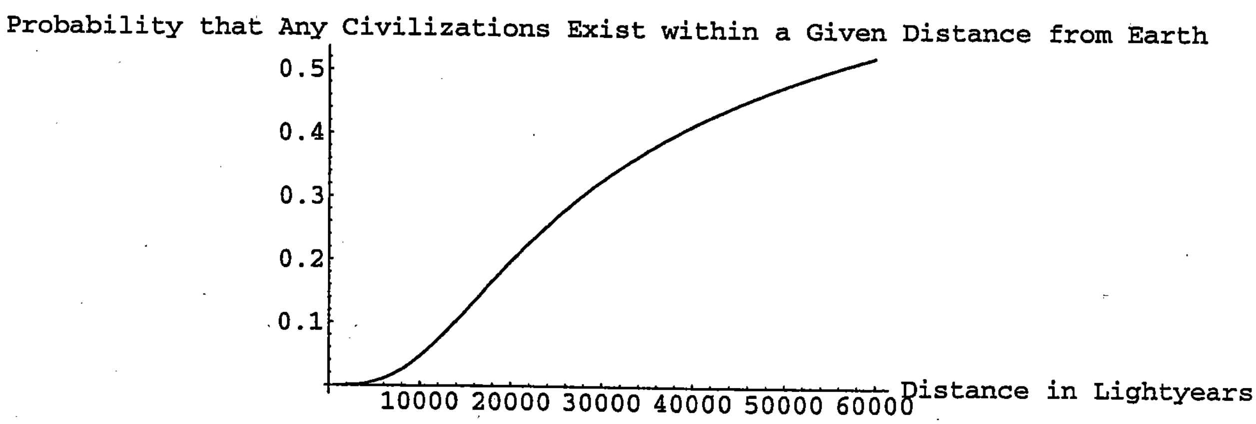
The following picture is probably instructive; it plots the probability that any civilizations presently exist within a specified number of light years from Earth. For example, there is a 50% probability that any civilizations exist if we go 55,000 light years from Earth.

REMARK. That the unconditional estimated distance is infinite may seem paradoxical. It is not paradoxical because the unconditional calculation was done by assuming an unbounded universe. Even for a finite universe, the infinite expected distance would not be contradictory; just think of the case that there are no civilizations in the entire universe. In such a case, the distance would have to be defined as infinity, and so the expected distance would be infinite as a corollary if there was a nonzero probability of there being no civilizations in the universe.

The combined conclusion of the estimated distance figures above is that if one were to take the model and the simulation with some credibility, then the hopes of detecting or contacting any companions are dim, at least in the present state of technology. And if indeed the civilizations are this much spread out, whether or not we accept the model and the simulation presented here, alien visits would likely be an impossibility for the eternal future. This would provide an answer to the famous FERMI PARADOX which asks: "if they are really there, why aren't they here ?" There is also a deep philosophical significance of such a thing; for every civilization in the universe would for ever live with the unanswered question whether THEY ARE ALONE!

7. SENSITIVITY ANALYSIS

It is desirable that some of the inputs in the theoretical model that we simulated be changed to see if the final conclusions can change radically. A fresh simulation of size 500 is presented here with a number of changes in the inputs of the theoretical model. Overall, with these fresh inputs, the final conclusions are a bit more optimistic , but not radically. This in spite of the fact that the inputs in this fresh simulation are quite a bit more favorable to more civilizations existing. We first outline which inputs are different and how they are different. Then we will report the results from this new simulation.


Probability that Any Civilizations Exist within a Given Distance from Earth
0.5
0.4
0.3
0.2
0.1
10000 20000 30000 40000 50000 60000
Distance in Lightyears

Quantity	What it was before	What it is now
$R(t)$	$S/T+$ a diffusion	Same; no change
H	$50 + 30*$ Beta $(4, 4)$	$50 + 30 *$ Beta $(5, 5)$
$Z_1, \dots, Z_5$	Exponential	Gamma, with means same as before
L_p	$U[5.5, 7.5]$	$U[4, 8]$
L	Expression (13)	Cauchy replaced by Normal $(0, \tau)$ with $\tau = .000125$; this makes the mean of that absolute normal 100,000 years, compared to a median of 10,000 years before, loosely speaking a ten fold increase
f_p	$U[0, .25]$	Same; no change
θ	$U[0, .01]$	$U[0, .1]$; ten fold increase
n_e	Poisson[.1]	Same; no change
f_l	1	$U[0, 1]$
f_c	$U[.7, 1]$	1
f_i	$U[0, 1]$	.5
f_a	$U[0, .5]$	Same; no change

REMARK: Thus, in this sensitivity analysis, L, θ, f_c are more favorable than before, and f_l is less favorable than before. L_p was made more uncertain than before, and f_p, f_i and f_a were not made either more or less favorable than before. The form of the distribution of $Z_1, \dots, Z_5$ was changed from Exponential to Gamma to impart some distributional robustness. Similarly, in L the Cauchy was changed to a normal with the same desire for a distributional robustness. The most drastic change is in θ, the proportion of sun-like stars, a ten fold more favorable input than before. H was changed slightly, but the star formation rate was kept the same because that is the quantity for which the best information are available. It is clear that a large number of the inputs were changed in some way or other; the sensitivity analysis is not fake.

Now we report the outcomes of this fresh simulation :

$$\text{Mean of } N_a \text{ over the 500 simulations} = 69.33$$

Median of $N_a = 15.14$

simulations having N_a as zero = 143

Standard deviation of $N_a = 124.006$

Quartiles of $N_a = 0, 15, 83$

Maximum of N_a over the 500 simulations = 1315

$P(N_a = 0) = 143/500 = .286$

80th %-ile of $N_a = 115$

90th %-ile of $N_a = 203$

95th %-ile of $N_a = 306$

99th %-ile of $N_a = 499$

Estimate of $\alpha = .21694$

Estimate of $\beta = .61031$

and,

Estimate of $E(d|N_a \geq 1) = 17701.1$ light years

Estimate of $E(d)$ (unconditional) $= \infty$

REMARK: We can see that although in this sensitivity analysis the measures pertaining to how many civilizations are present in the galaxy are surely higher than before, the estimated distance to the nearest one continues to be still very very high. In terms of detection or contact, 17,700 light years would still be far too far at the state of the tech nology in the near future. Thus that important aspect did not really change in any practically consequential way from the first simulation to the next. In addition, in each case the unconditional expected distance is estimated to be infinite, as in both cases the α parameter is estimated to be $< 1/3$.

Let me finish the main part of this article with a general formula for $E(N_a)$ under the Drake equation model. The purpose of the formula is to equip a reader with an expression into which he or she can use a personal set of parameters to obtain a personal value for the expected number of civilizations existing at the present time in the galaxy . To state this formula, we need a little more notation in addition to the notation already used.

In equation (13), in specifying the distribution for L, assume that $L \sim \max[0, \min\{W, L_p -$

$\sum_{i=1}^{5} Z_i\}]$ for some specific W (we had used an absolute Cauchy or normal for W. Let also f and F denote the pdf and the cdf of W. Let also λ denote the rate of extinction events (we had used $\lambda = 40$ or 25) and μ_4 the mean of Z_4. The formula for $E(N_a)$ is as follows:

Result 8.

$$E(N_a) = \frac{1}{1+\lambda\mu_4 p_{ex}} E[R(1-f(R)) + \int_0^R wf(w)dw] \\ * E(P_h(t))E(f_l)E(f_c)E(f_i)E(f_a), \qquad (23)$$

where $E(P_h(t)) = \varepsilon E(\theta)E(f_p) \times 23.66 \times 10^9$, and R stands for the random variable $\max[0, L_p - \sum_{i=1}^{5} Z_i]$. In this formula, the part $E[R(1-F(R)) + \int_0^R wf(w)dw]$ would have to be evaluated by a monte carlo simulation for R on specifying one's distributions for L_p and $Z_1, \ldots, Z_5$. For example, we had exponential distributions for $Z_1, \ldots, Z_5$ with means .3, .5, 3, 1 and .1 and $L_p \sim U[5.5, 7.5]$. Furthermore, if we use an absolute Cauchy for W, then $f(w) = \frac{2}{\pi(1+w^2)}$ and $F(R) = \frac{2}{\pi}$ arctan (R). Monte carlo gave the needed expectation to be .000065. For example, as an illustration, if one uses

$$\left.\begin{aligned} \varepsilon &= .1 \\ E(\theta) &= .05 \\ E(f_p) &= .1 \\ \lambda &= 30 \\ p_{ex} &= 10^{-8} \\ E(F_l) &= .5 \\ E_{f_c} &= .5 \\ E_{f_i} &= .5 \\ E_{f_a} &= .25 \end{aligned}\right\}$$

then $E(N_a)$ works out to 24.03. Again we come up with a number that is not in the billions or millions, but in the low range. I invite the reader to use formula (23) with his or her choice for all the parameters and also the choice of his or her distributions for L_p, $Z_1, \ldots, Z_5$ and W. I hope it will be instructive.

FINAL REMARKS

At long last, it now seems to be the time to make some final remarks about what we seem to have found. We used the universally accepted paradigm of the Drake equation, and we made an attempt to be as unbiased and imprejudiced as we could in modelling the factors of the Drake equation. There is nothing like a correct model in a problem like this; only reasonable models. We tried a reasonable model, and even did a sensitivity study. The conclusion is that if there are any civilizations in our galaxy at the present time, the number is not in the order of millions or billions or even thousands. They are much less, and the simulations would suggest there could actually be very few. Furthermore, the distance to the nearest one, according to the simulation and the supporting sensitivity study, is so large that we need to be much more prudent about the chances of making a contact, or meeting them. If I could be allowed a moment of philosophy at the end of this long article, it does seem that the galaxy and perhaps the universe is a symphony of God with truly long silences, aloneness and isolation being the destiny of man and his companions, wherever they are.

8. TECHNICAL APPENDIX

Result 1. Due to this result, we can start the simulation of the model with $P_h(t)$, avoiding the need to simulate $S_s(t)$ etc., which would require simulation of the Ornstein-Uhlenbeck process. Do note, however, the correlation is ignored; the simulation would be very time consuming otherwise.

By definition, $P_h(t) = \sum_{i=1}^{S_p(t)} n_{e,i}$ where $n_{e,i}$ are iid, distributed as Poisson (ε). Thus,

$$\begin{aligned}
E(P_h(t)) = \varepsilon E(S_p(t)) &= \varepsilon E E(S_p/S_s, \theta_p) \\
&= \varepsilon E(\theta_p S_s) \\
&= \varepsilon E(\theta_p) E(S_s) \text{ (by their independence)} \\
&= \varepsilon E(\theta_p) E(\theta \frac{.455H}{U^2} + X(t)) * 10^9 \\
&= \varepsilon E(\theta_p) E(\theta) * .455 * 65 * .8 * 10^9 \\
&\quad \text{(as } E(\frac{1}{U^2}) = .8 \text{ if } U \sim U[1, 1.25]) \\
&= \varepsilon E(\theta_p) E(\theta) * 23.66 * 10^9; \qquad (23)
\end{aligned}$$

if we use $E(\theta_p) = .125$, $E(\theta) = .005$ and $\varepsilon = .1$, we obtain $m = 1.47875 * 10^6$.

To obtain the value of v, first one obtains the second moment

$$E(P_h^2(t)) = \varepsilon E(P^2(t)|S_p) = E(\varepsilon S_p(t) + \varepsilon^2 S_p^2(t))$$
$$= \varepsilon E(\theta_p)E(\theta) * 23.66 * 10^9 + \varepsilon^2 EE(S_p^2|S_s, \theta_p) \tag{24}$$

But $E(S_p^2|S_s, \theta_p) = S_s(t)\theta_p(1-\theta_p)+\theta_p^2 S_s^2(t)$. Now use the representation $S_s(t) = \theta(\frac{.455H}{U^2} + X(t)) * 10^9$, where $X(t)$ is the Ornstein-Uhlenbeck process. Squaring this and taking the expectation results in $E(S_s^2(t)) = 573.52 * E(\theta^2) * 10^{18}$; also $E(S_s(t)) = 23.66E(\theta) * 10^9$. Plugging all of this into (24) will give

$$E(P_h^2(t)) = (\varepsilon E(\theta_p) + \varepsilon^2 E(\theta_p)(1-\theta_p))E(\theta) * 23.66 * 10^9$$
$$+ \varepsilon^2 E(\theta_p^2)E(\theta^2) * 573.52 * 10^{18}, \tag{25}$$

from which $v = 1.7500 * 10^{12}$ obtains by doing the arithmetic for $v = E(P_h^2(t)) - m^2$, with $E(\theta_p) = .125$, $E\theta_p(1-\theta_p) = .1042$, $E(\theta_p^2) = .0208$, $E(\theta^2) = .000033$ and $\varepsilon = .1$. That $P_h(t)$ is approximately normally distributed follows from the Doeblin-Anscombe central limit theorem for sums of random numbers of independent random variable (see pp. 322, Chow and Teicher (1988)).

Result 2. For both Result 2 and Result 3, we will need the general result that if X, Y are nonnegative random variables with CDF F and density g respectively, then $P(X+Y \leq t) = \int_0^t F(t-y)g(y)dy$. For Result 1, $F(x) = 1 - e^{-\frac{x}{\mu_1}}$ and $g(y) = \frac{1}{\mu_2}e^{-\frac{y}{\mu_2}}$. Integration will give

$$P(Z_1 + Z_2 \leq t) = 1 - \frac{\mu_2 e^{-\frac{t}{\mu_2}} - \mu_1 e^{-\frac{t}{\mu_1}}}{\mu_2 - \mu_1}, \tag{26}$$

and hence $P(Z_1 + Z_2 \leq L_p)$

$$= \frac{1}{b-a}\int_a^b (1 - \frac{\mu_2 e^{-\frac{t}{\mu_2}} - \mu_1 e^{-\frac{t}{\mu_1}}}{\mu_2 - \mu_1})dt$$
$$= 1 - \frac{\mu_2^2(e^{-\frac{a}{\mu_2}} - e^{-\frac{b}{\mu_2}}) - \mu_1^2(e^{-\frac{a}{\mu_1}} - e^{-\frac{b}{\mu_1}})}{(b-a)(\mu_2 - \mu_1)}$$

Result 3. The proof is similar to that of Result 2 and so we omit it.

Result 4. A civilization that has originated exists at the present time instant T if the parent star corresponding to that civilization originated at a time t which meets the requirements $t+Z_1+Z_2+Z_3+Z_4+Z_5 < T < t+Z_1+Z_2+Z_3+Z_4+Z_5+L \Leftrightarrow t_L < t < t_U$ with t_L and t_U as in the statement of Result 4.

Result 5. We will obtain the expression for $E(d|N_a \geq 1)$ by evaluating it as

$$E(d|N_a \geq 1) = \int_0^\infty P(d > r|N_a \geq 1)dr. \tag{27}$$

To obtain $P(d > r|N_a \geq 1)$, we will have to use the assumption that civilizations (which we will call events) are distributed according to a compound spatial Poisson process, i.e., conditional on λ, the number of events in a region A of space of volume $V(A)$ is Poisson distributed with mean $\lambda V(A)$, and λ has distribution G. If we denote the Milky Way galaxy as S, then N_a is just the number of events in S. It is known that S has diameter 100,000 light years, and Earth is 30,000 light years from the galactic center. By changing the unit to 10,000 light years, we have S with a diameter of 10 and Earth at a distance of 3 from the center of S. To derive the stated formula for $E(d|N_a \geq 1)$ we will pretend, that S is spherical; this is definitely not true, but no such formula for $E(d|N_a \geq 1)$ would be possible for an odd shaped S.

Recall that we need

$$\begin{aligned} &P(d > r|N_a \geq 1) \\ &= \frac{P(d > r, N_a \geq 1)}{P(N_a \geq 1)} \\ &= \frac{P(d > r) - P(d > r, N_a = 0)}{1 - P(N_a = 0)} \end{aligned} \tag{28}$$

In (28),

$$\begin{aligned} P(N_a = 0) &= P(\#\text{ events in } S = 0) \\ &= \int e^{-\lambda V(S)} dG(\lambda) \\ &= \int_0^\infty e^{-\lambda * \frac{4}{3}\pi(5)^3)} \frac{e^{-\frac{\lambda}{\beta}}\lambda^{\alpha-1}}{\beta^\alpha \Gamma(\alpha)} d\lambda \\ &= \frac{3^\alpha}{(3+500\pi\beta)^\alpha} = \eta(\text{say}). \end{aligned} \tag{29}$$

Now the event "$d > r$" simply means that in a sphere $B(y,r)$ centered at y, the location of Earth, and of radius r, there are no events. Furthermore, for $r \le 2$, $B(y,r) \subset S$ as y is at distance 3 from the center of S and S has radius $= 5$. Hence for $r \le 2$, $P(d > r, N_a = 0) = P(N_a = 0) = \eta$. As well, for $r \ge 8$, $S \subset B(y,r)$ and so $P(d > r, N_a = 0) = P(d > r)$ $= \int e^{-\lambda \frac{4}{3}\pi r^3}\, dG(\lambda) = \int_0^\infty e^{-\lambda \frac{4}{3}\pi r^3}\, \frac{e^{-\frac{\lambda}{\beta}}\lambda^{\alpha-1}}{\beta^\alpha \Gamma(\alpha)}\, d\lambda$

$$= \frac{1}{(1 + \frac{4}{3}\pi r^3 \beta)^\alpha}. \qquad (30)$$

For $2 < r < 8$, we need to find $P(d > r, N_a = 0)$ as follows.

$$\begin{aligned}
&P(d > r, N_a = 0) \\
&= P(\text{There are no events in } S \text{ or } B(y,r)) \\
&= \int e^{-\lambda \text{ volume } (S \cup B(y,r))} dG(\lambda) \\
&= \int_0^\infty e^{-\lambda[\frac{4}{3}\pi (5)^3 + \frac{4}{3}\pi r^3 - \text{ volume } (S \cap B(y,r))} \frac{e^{-\frac{\lambda}{\beta}}\lambda^{\alpha-1}}{\beta^\alpha \Gamma(\alpha)} d\lambda. \qquad (31)
\end{aligned}$$

By transforming to polar coordinates, the volume of the intersection of the spheres S and $B(y,r)$ can be found as $\frac{2\pi(r+2)^2(12r-12-r^2)}{24}$ (here is where the sphericity assumption for S is convenient). Plugging this into (31), one would get:

$$\begin{aligned}
&\text{for } 2 < r < 8, P(d > r, N_a = 0) \\
&= \frac{1}{(1 + \frac{\beta\pi}{12}(r+8)^2(32 - 8r + r)^2)^\alpha} \\
&= p(\alpha, \beta, r) \text{ (say)} \qquad (32)
\end{aligned}$$

Putting it all together, from (28),

$$\begin{aligned}
&E(d|N_a \ge 1) \\
&= \frac{1}{1-\eta}[\int_0^2 (P(d > r) - \eta)dr + \int_2^8 (P(d > r) - p(\alpha,\beta,r))dr \\
&= \frac{1}{1-\eta}[\int_0^8 P(d > r)dr - \int_2^8 p(\alpha,\beta,r)dr - 2\eta \\
&= \frac{1}{1-\eta}\int_0^8 \frac{1}{(1 + \frac{4}{3}\pi r^3 \beta)^\alpha}dr - \int_2^8 \frac{1}{(1 + \frac{\beta\pi}{12}(r+8)^2(32 - 8r + r^2))^\alpha}dr - 2\eta], \qquad (33)
\end{aligned}$$

giving the needed expression.

Result 6. Follows easily on integrating $\int_0^\infty P(d > r)dr$.

Result 7. Straightforward.

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