COMETS, INFORMATION, AND THE ORIGIN-OF-LIFE

ROBERT B. SHELDON
National Space Science & Technology Center,
320 Sparkman Dr, Huntsville, AL 35805

Abstract

The triumph of Democritean materialism over biology in the 19th century was tempered in the 20th by the discovery that time was not eternal and that life was too complicated to spontaneously organize. This led to the paradox of assuming only material causes for life's origin while making them practically impossible. We address this 150 year-old origin-of-life (OOL) problem by redefining it as an information threshold that must be crossed. Since Shannon information has too little capacity to describe life, we expand it to include time and correlated information. Generalized to Einstein's spacetime, we show that information capacity implies information flow, and flows imply an "ether," a material carrier. From recent discoveries of fossilized microbial life on carbonaceous CI1 meteorites whose D/H ratios, albedo, and elemental abundance are all cometary, we identify the material carrier with comets. With sufficient cometary density, which we hypothesize may be supplied by the missing galactic dark matter, non-linear correlations amplify the probability that comets can assemble life from distributed information sources. If information is conserved, as suggested by many cosmologists, then this distributed information source becomes the boundary condition of the 4-sphere describing the Big Bang. Recent advances in theoretical physics suggest that the assumption of the conservation of information along with the conservation of energy are sufficient to derive Newton's laws, making materialism a corollary of information, and the OOL a trivial result of imposed Big Bang boundary conditions as transmitted through the cometary hydrosphere.

1. Introduction

The origin-of-life (OOL) problem has been traditionally viewed as a informational barrier, whereas comets, when they have been considered at all, have been treated as passive, information-neutral carriers of life. In this paper we attempt to show how OOL and comets form a synergistic system, involving both information and transportation.

1.1. THE ORIGIN-OF-LIFE PROBLEM

After Darwin's success (Darwin 1859) at reviving Lucretius' Materialism (Lucretius Carus 1921) with its rejection of teleological or vitalist explanations for evolution (Davies 2000), there arose a paradox on the origin of that first life. On the one hand, Darwin rejected any inherent property of matter that made it alive; it had to be a naturalistic spontaneous generation from non-life. But on the other hand Pasteur demonstrated that life always came from life, that spontaneous generation did not easily occur (Pasteur 1861; Farley 1974). Darwin acknowledged the problem, but merely expressed a belief that under the right conditions (a warm pond) and with sufficient time (eternity), spontaneous generation could still be likely (Darwin 1887; Peret et al. 2009).

Subsequent discoveries have not been kind to Darwin's estimate. The age of the universe has shrunk from eternity to 13.7 Ga (Komatsu et al. 2011), and the complexity of the first living cell has grown astronomically from the "protoplasm" imagined by Darwin to the complexity of modern biochemistry (Meyer 2009). Despite early evidence of the liquid water environment, a complete set of cellular nanomachines needed for life would require extensive assembly and dynamic initialization (Polanyi 1968). To expect a proper assortment of pieces to randomly assemble is estimated in various places to have a probability of less than one in 10^{41000} (Hoyle and Wickramasinghe 1981a, 1981b, Hoyle 1999). These are not even astronomical, these are cosmological improbabilities, as illustrated by the following example.

Suppose that the J. Craig Venter Institute (www.jcvi.org) is successful in producing a stripped-down Mycoplasma with a mere 1000 codons describing a minimally functional 1000 amino-acid protein set (and substantially shorter than their synthetic *M. mycoides JCVI-syn1.0* genome with 991,920 codons, Gibson et al. 2010, Wickramasinghe et al. 2003, Wickramasinghe 2011). Further supposing one had a computer that generated random arrangements of 1000 codons and then tested each for possible "life," how long would it likely take to find the right arrangement, where "likely" is a probability of one-half? Since there are 20 possible amino acids, a 1000 long chain has $20^{1000} = 10^{1301}$ permutations. Supercomputers today are capable of "petaflops" or a million billion instructions per second (Oak Ridge National Laboratory 2009). There are ~31 million seconds in a year, so if each instruction is a test of a random sequence, we have about 10^{22} evaluations in a year. At this rate, 10^{1301} tests would take 10^{1279} years, or much longer than the 10^{10} years that the universe has existed.

We know that computer chips are getting faster and smaller, so could such a computer be built in the future, even if it is impossible today? There are physical limits on speed and size, the most rigorous physics limit being the "Planck time" given by quantum mechanics for the shortest interval of time that has any meaning, or about 10^{-43} seconds. Then the maximum number of time intervals from the beginning of the universe is 13.7 Gyr * $3.1\text{x}10^{7}$ sec/yr * 10^{43} intervals/sec $=10^{61}$ intervals. We will further assume that at least one electron or elementary particle has to be involved in a calculation so the maximum number of computable bits must be no greater than the number of particles in the universe, or about 10^{80}. Their product is 10^{141} maximum computer calculations, assuming the entire universe were an atomic computer (Dembski 1998). More careful estimates applying the limitations of general relativity on the quantum physics give the computational capacity, or stochastic resources of the universe, to be about 10^{120} operations on 10^{120} bits (Lloyd 2002).

This result sums up the current impasse in OOL research: randomly generating the proper arrangement of even a 1000-peptide enzyme is outside the computational abilities of the universe, much less the 991,920 long minimal genome of *Mycoplasma.* So not only has it proved difficult to create life in the laboratory, or even find a mechanism to spontaneously generate it, but theoretically it appears hugely improbable that a random search can ever find it.

One counter-argument to these cosmological improbabilities is to argue that there are many more arrangements of the basic building blocks that are alive. That is, just because the minimal life form we chose has a specific arrangement of 1000 amino acids representing a one in 10^{1301} probability, doesn't mean that there aren't 10^{1270} other arrangements of those 1000 amino acids that are also "alive." Thus the OOL computation need only find one of those other possible permutations, which would increase the odds and make spontaneous generation feasible.

The counter-counter argument, is that the putative ubiquity of "living" permutations should cause spontaneous generation to be observed frequently, which it hasn't (Pasteur 1861; Hoyle and Wickramasinghe 1981a, 1981b, Hoyle 1999). Or it should leave behind a body of alternate forms for these basic proteins and gene coding, which it hasn't (Meyer 2009). Furthermore, a laboratory that randomly permutes enzymes and genomes should frequently produce viable organisms, which also hasn't happened (Barrick et al. 2009). Rather, mapping out the viable organisms in "permutation space," reveals a tremendous desert of nonviable arrangements (Axe 2004). Life appears to be highly specific, ordered, and particular, which puts severe limits on the ease of randomly making life.

An alternative counter-argument suggests that we live in a "space" of many universes, each one birthed by random fluctuations of the vacuum. Since a fluctuation has a certain "Planck-length" volume, then at any given instant, the universe can be divided into cubes of size 10^{-35} m, or about $[10^{61}]^3$ cubes today. If we argue that a new universe can form in one Planck time, and each universe can spawn more universes, then we have an exponential series from our Big Bang onward, (1 the first instant, 2^3 the next, up to $[10^{61}]^3$) for a total less than 10^{243} "similar" universes (Guth 2007; Susskind 2007). String-theory with its 11 dimensions achieves a larger number of about $[10^{61}]^{11}$, though Linde believes this number to be surpassed by entropy considerations of the cosmological constant, or about 10 to the power 10^{82} universes (Linde and Vanchurin 2010). Of course, our universe might have begun unmeasured years after some "original" Big Bang, so in principle the number of multiverses in the "landscape" may be infinite and time eternal.

There are numerous difficulties with the scenario sketched out above. For example, once infinite solutions are posited, it is difficult to find any single solution, because the fastest growing solution becomes dominant, so the discussion changes from finding our universe to the difficulty of demonstrating why ours has the fastest growth rate in an infinite set. And since a directed search is faster than a random search, the fastest growing solution would also be the most teleological, which contradicts the materialist assumptions. For example, suppose in one of those infinite universes there comes into existence a being with the ability to communicate between multiverses giving it immense computational resources and allowing it to inject information into any particular universe much faster than random chance can produce it. By the usual definitions this behavior would be supernatural, thus making the entire justification of the multiverse hypothesis–the naturalistic production of life–impossible. This argument can be made more rigorous using Gödel's method of enumerating the infinite worlds (Gödel,1931), demonstrating any subset of "materialist multiverses" is still incomplete.

Ignoring this incoherence of infinities, there is significant doubt that universes can actually appear in the vacuum as hypothesized, since energy is not conserved in this model (Pitts 2010). Furthermore, the minimal life recorded by Venter has combinatorial information at least $20^{991,920}$($=10^{1,290,517}$) not including the dynamical information and the permutations of "fine tuned" physical constants that add at least another factor of 10^{1000}. Nor is it clear that each multiverse would sample the solution space evenly, or even whether dynamically interacting systems can be constructed from non-interacting random steps. Thus it would appear that the multiverse solution of reintroducing Democritus' infinities produces more problems than it solves.

The arguments and counter-arguments do not agree on the density of viable arrangements in protein phase space, they do not agree on the minimum codon length needed for life, or even the nature of the universe. But this lack of agreement should not distract us from recognizing two common characteristics of the debate: first, the OOL problem involves astronomical probabilities in which incremental progress is measured in factors greater than ten billion (10^{10}); and second, a successful OOL theory hinges on ways to bring these astronomical probabilities down to Earth. In this paper, we argue that comets can address both goals, though not without cost.

1.2. THE COMETARY HYDROSPHERE

Over the past century, it has become increasingly apparent that life does not reside solely on this planet Earth, (e.g., Arrhenius 1908) but probably exists throughout the Solar System wherever there is liquid water as on moons or planets (Levin and Straat 1976; Coates et al. 2010; Strobel 2010; NASA/Jet Propulsion Laboratory 2010), but more importantly, on numerous, small icy bodies, called comets when they cross Mars orbit, melt, and acquire visible tails (Hoyle and Wickramasinghe 1980, 1981a, 1981b, 2000). Recent discoveries of fossilized life on carbonaceous chondrite meteorites thought to be extinct comets also support comets as unique (Hoover et al. 2004, Hoover 2008, 2011). Comets distinguish themselves in several ways from rocky bodies: they have short "summers" when they come near the Sun and melt followed by long "winters" far from the Sun when they refreeze; they explore a much larger volume of space in their orbit; they accrete material along their orbit, their "lifespan" is much shorter with a "death" involving disintegration into many smaller fragments; and they are frequently ejected from the Solar System gravitational well (Sheldon and Hoover 2005, 2006, 2007). These properties of the cometary "life cycle" are so different from the gravitationally bound rocky bodies that we call this wide range of sizes, temperatures, and orbits "the cometary hydrosphere."

Supposing that a significant fraction of melted comets become infected with life, then the cometary hydrosphere is also a cometary biosphere that is able to survive, spread, and transport life across the galaxy, possibly from the moment when stars began to form 12 billion years ago (Sheldon and Hoover 2008). This potential cometary biosphere can then interact with the OOL problem in several important ways. For example, since comets can transport life between rocky bodies, then if life is found on different planets, it is not necessary to hypothesize that life began independently twice, for it could have begun on either rocky body and spread to the other, or even begun on comets and spread to the rocky bodies. Therefore transportation changes the OOL problem by permitting a much larger volume of space to be involved. But transportation does more than allow a greater volume of the universe to be involved, it also allows a greater timespan (distance divided by comet velocity) to be involved. Thus comets integrate the entire volume of the galaxy into the OOL problem (with a smaller probability for multiple galaxies) over nearly the entire time since the Big Bang.

If we hypothesize that the OOL probability (OOLP) scales as the probability of a rare event times the number of locations and the amount of time, then this inclusion of a galaxy of locations existing over the entire time since the Big Bang increases OOLP by approximately 10^{24} compared to the probability of forming only on Earth. This number can be estimated very roughly by calculating the ratio of Earth OOLP to cometary OOLP, which means comparing the ratio of time intervals and volumes available for life to begin on Earth, to that on comets.

Calculating the maximum amount of time available for Earth OOL gives a time interval between the molten-rock Hadean Age at the end of the planetary bombardment of 3.85Gyr BP and the first appearance of bio-fractionated carbon at 3.65 Gyr BP (Mojzsis et al. 2003), or about 200 million years. A similar calculation for cometary OOLP starts from star formation some 12 Gyr BP to the same spot or about 8 billion years. Then the ratio of time intervals for cometary/Earth OOLP is about 40 times larger.

Likewise, an estimate for the volume of cometary water around the planet Earth since the Hadean is approximately equal to the volume of ocean water in the planet Earth today (Sheldon and Hoover 2007). If each star system has a similar amount of cometary water, then we can multiply by the number of stars in the galaxy (and assuming no other rocky planets with oceans) which gives about 100 billion times more volume in galactic comets than on the Earth. If we further assume that other galaxies were accessible by comet (which is uncertain, because the high velocities of intergalactic comets needed to cover the distance preclude capture into the gravitational well of a target solar system), we can increase this number by another 100 billion to account for the number of observable galaxies in the cosmos. Then the ratio of volume cometary water over Earth water increases the cometary OOLP by about 10^{22}. Finally, combining the time and volume ratios gives a rough estimate of a 10^{24} increase in cometary over Earth OOLP.

We could increase this slightly by assuming a distribution of rocky bodies with liquid water oceans throughout the galaxy, but all these refinements hardly change this number by more than one order of magnitude, which when compared to estimates of Earth OOLP<10^{-1301}, provide insufficient progress in solving the OOLP puzzle. Note that these refinements are all "linear adjustments" to the OOLP calculation, scaling directly with volume and time interval. As we discuss later, it is enticing to consider whether the 70% "dark matter" of the universe is composed entirely of comets, in which case, we would have to increase our estimate of the cometary hydrosphere by another factor of about 10^7, and yet would have made little progress on raising OOLP close to 1/2. That is, assuming the most radical changes to cosmology that incorporates every cubic centimeter of potential water into the OOLP calculation, would hardly move the resulting probability.

These sorts of considerations suggest that the OOL problem will not be solved by tweaking linear factors. If time and space are only linearly correlated to OOLP there will be no solution, however, there may yet be non-linear corrections to OOLP made possible by the discovery of the cometary hydrosphere.

2. Origin-of-life Probability and Linearity

One of the many difficulties in discussing the OOL problem, is that we confuse the theory with the practical, or the immaterial with the material. The combinatorial problem of OOLP is theoretical, because no chemical reaction, no cellular biochemistry proceeds in the manner described. For example, when Venter announced his synthetic bacteria (Gibson et al. 2010) using non-organic deoxyribonucleic acid (DNA) machine-manufactured from biologically derived reagents, the DNA fragments by themselves were useless. So they inserted these fragments into a living yeast cell so as to reassemble the 1078 pieces, and injected that repaired DNA into a related bacterial species whose own DNA had been removed. One hurdle that took many months to solve was a result of a single missing codon. Nowhere in this experiment was there a theoretical problem similar to the combinatorial math of the OOLP problem, rather, all the biological protein machines were running and operational when the sleight-of-hand to change out the DNA occurred. Venter's success was not randomly finding a sequence, but rather converting the immaterial logical sequences into living biological material.

The combinatorics assumes that there is a fixed target that we are to search for blindly, like a needle in a haystack, whereas the Venter problem was to swap one DNA for another in a living organism, reminiscent of electricians who rewire factories without turning off the power. The Venter approach began with a living chemical environment and tries to change it without killing it, whereas the combinatorial approach began with a dead chemical environment and hopes to enliven it without trying. The latter is an attempt to find life without a driver, whereas the former is an attempt to keep life going while switching drivers.

If we know the sequence we are after, then like the Venter Institute, we can produce that DNA after due attention to quality control. But if we don't know the sequence, it will take a very long time to find it. The OOLP problem has been stated as the difficulty of randomly finding the right sequence. Many computational biology approaches have been proposed as "smart" algorithms for finding the "living" sequence, but as Dembski argues, all these programs—*Weasel* (Dawkins 1986), *Ev*, or *Avida*—smuggle in information that helps with the search (Dembski and Marks 2010). In fact, the "No Free Lunch" theorem proves that without prior information, there is no "smart" algorithm that can outperform a random search, which is where we started our discussion (Dembski 2002).

But perhaps the problem is assuming some sort of maximally random "warm pond" as the starting point, and attempting life in one step. If an information-rich substrate, perhaps a clay, or a coacervate, permits the addition of information that leads to OOL, then the formation of life is much closer to Venter's problem, that of adding information without losing what is already there. That is, the "smuggling" of information, which is the bane of Dembski's algorithmic analysis, represents the pinnacle of Venter's experimental accomplishment.

For the OOLP calculation does not need to begin at zero and in one jump make it to *Mycoplasma*, rather, it may be possible to combine two information-rich subsets–say coacervates and ribonucleic acid ribozymes–to produce life. So both "smuggling" and "finding" contribute to OOLP. We are not saying that breaking down an improbable string into substrings changes the probability of forming the final string, only that smuggling or "adding up substrings" possesses probabilities as important to OOLP as finding the final string. The OOL problem is exacerbated, not reduced, by including the probability of experimentally adding information. For as the Venter Institute reported, it was quite difficult to add information, requiring real reagents manipulated in vitro with real organisms, rather than the manipulation of abstract symbols on a computer.

Since OOLP is proportional to the probability of finding the minimal sequence multiplied by the probability of the method producing that sequence, the information from experimental production of the proper sequence is just as important as the information in the sequence. Since there are a great many ways to make substrings and add them together, each with its own probability, OOLP must be the most probable method selected from all the possible paths to that destination. That is to say, while we cannot make the discovery of a long string of peptides more probable by breaking it into substrings, we can make the manufacture of that string of peptides more probable by breaking it into substrings. And non-linear production mechanisms have the potential to be the most probable.

If it is comets that transport the reactants for OOL, then just as a dimerization reaction proceeds at a quadratic or non-linear power of the density of reactants, so also the density of comets functions as a non-linear factor both in the abiotic (purely chemical) OOL pathway as well as in the biotic or quasi-biotic evolution pathway. Debate over where to place the pre-biotic versus biotic boundary is irrelevant, for whatever non-linear mechanism we invoke should still generate sufficient probability to overcome the difficulties of addition. Comets fulfill this role nicely, providing the non-linear delivery of reactants for an abiotic OOL synthesis or the non-linear delivery of genes for biotic evolution. In both cases, it is a density-dependent non-linear function that has the potential to approach an improbable OOLP.

3. Information Restatement of OOL

Despite the simplicity of modeling life on the molecular reactions needed to produce a living sequence, it would be inaccurate to quantify OOLP only by the density of reactants, which ignores the hidden effort of the biochemist, who, when abiotically synthesizing an important biochemical, carefully isolates the products from the reactants, performing several purifying steps for every synthesis step. Quantifying these actions of the chemist is analogous to a physicist's calculation of entropy. That is, purification produces no new products, but does reduce the entropy of the products at hand. The inverse of entropy is information, so whenever making an OOLP calculation, it would seem convenient to keep track of the information content, whether added by purification or added by increasing codon length.

In fact, it would be mathematically advantageous to cast the entire OOLP problem as a problem of information, where life is assumed to be a highly informational state of matter. Then one could calculate OOLP quantitatively over the entire space from the low-information dilute chemicals to the high-information life, from the beginning of the time interval to the end.

This recasting of the OOL problem as a change in information content has several other advantages as well, making it independent of material details (viruses versus cyanobacteria) or temporal details (RNA-world versus metabolism-first). We merely set some informational threshold, and argue that when the information in the system exceeds that threshold, we have OOL. Since life also concentrates that information into a small volume, we should restate the threshold as an information density spike achieved somewhere in our volume. This is still not quite right, because a dead bacterium may have the same information density as a live bacteria, yet be completely unable to propagate, and therefore not "alive." So we should further refine our threshold to include time or information density flow, where spatial derivatives are used to establish the density, and temporal derivatives determine the flow.

If this information density is so very improbable, then the exact level of the threshold is unimportant, because the gradients in space and time should be so very steep. If information is measured in "probability units," we could set it at 10^{150}/cubic micron or at 10^{15000}/cubic micron with no real difference to the outcome. Likewise, the diffusive entropy flow should be enormous at sharp gradients, so the mere fact that a cell doesn't rapidly dissipate with time is a signature of strong informational flow. The entropic dissipation is a function of the strength of the gradient and the local temperature, so for the ease of computation, we normalize the information flow to the expected gradient driven dissipation flow, with life demonstrating a flow of opposite sign to dissipation, and slightly greater than the expected dissipation flow. Note that for freeze-dried or lyophilized bacteria, the entropy flow is so very small that the countercurrent of living information flow may be virtually undetectable, but nevertheless exist even in a state of suspended animation.

This discussion has been necessarily qualitative, but considering the many orders of magnitude involved in the OOLP calculation, we do not think we have oversimplified the problem yet. The OOL problem can then be restated as the appearance of very high informational density that also has an informational (negative entropic) flow slightly larger than the expected positive entropic decay rate. Calculating this quantity, then, will require a calculation of information density over all space and its time evolution (or temporal derivative). In the next section we discuss this calculation mathematically.

3.1. SHANNON INFORMATION IN SPACETIME

In a series of ground-breaking papers, Shannon developed "Information Theory" from scratch, developing it to describe the carrying capacity of telephone cables, and then applying it to the English language as a paradigm case (Shannon 1948; Shannon and Weaver 1949). In the ensuing development of the mathematical theory, there tends to be two simplifying directions of his research: calculating the information capacity (spatial derivative of the telephone cable); and calculating the informational flow (temporal derivative of the signal).

As an example to clarify the difference between capacity and flow, consider the coaxial cable used to bring cable television into a house, which has a higher capacity than copper twisted pair. While possessing less capacity, over time the bit rate of twisted pair went from a 300 bits-per-second (bps) acoustic modem, to a 1200 bps digital modem, to 9600 bps "maximum" for vocal frequencies, to 56 kbps for digital compression. Each time a new modem arrived we were told this was the theoretical maximum for twisted pair, yet today we have twisted pair carrying DSL at 1-4 Mbps. This increase in bandwidth is not a function of time-independent geometry, as seen in the coax versus twisted-pair comparison, but a function of frequency and compression algorithms that are able to make each bit carry more information by relating it to the bits before and after it. Making a graphical analogy to water pipes, the coax is a wider pipe than twisted-pair, whereas the improvement in twisted-pair modems is a faster flow or greater pressure. Therefore information theory involves both a spatial and a temporal component, which are related by the speed of the information carrier: electricity for telephones, sound-waves for liquids, chemical-waves for biochemistry, and comets for astrophysics.

What exactly is this information which Shannon described? Shannon began by characterizing the noise on the telephone line as a binary bit stream. Noise comes from fluctuations, which may be described by their frequency dependence: a Gaussian distribution is thermal, or a flat distribution is "white", and a 1/frequency distribution is "brown". Whatever the noise distribution, the signal is what remains when the noise is subtracted out, which means that the signal is strongest on the "wings" of the Gaussian, where the more improbable the noise, the better the signal/noise ratio. As the number of particles gets larger, and a mole of molecules is already 10^{24}particles, these Gaussians get extremely steep, making it much easier to manipulate the logarithm than the quantity itself. Boltzmann defined entropy, S, to be his constant, k, time the logarithm of the number of states in distribution, $ln(\Omega)$, (and had the equation $S=k\ ln(\Omega)$ engraved on his tombstone). Shannon's definition of information, I, is just the negative of Boltzmann's S, or what he called "negentropy."

Relating this negentropy to the distribution of chemicals in a warm pond, a smooth and dilute distribution is the most probable, and hence the "noisiest" or most entropic distribution, whereas a concentrated spot of chemicals is the least probable and therefore the higher negentropy information content. Using the appropriate scale length, we might say that the information in a particular dissolved chemical is its local concentration divided by the expected average concentration. But note that this is a time-independent measure, this is the "width" of the information pipe, not its "pressure."

To calculate the information "pressure" of this chemical concentration gradient, we have to compare it to the state immediately before and the state immediately after. If the states are describable by a simple law, say, the diffusive motion of a chemical gradient, then the entropy increases, and the information decreases. If, however, there is no physical law that connects these states, or more precisely, the greater the deviation from the physical law of diffusion ($df/dt = D\ d^2f/dx^2$), the greater the information content in these adjacent states.

Shannon does this calculation in a 1951 paper on the information content of written English (Shannon 1993). To calculate the spatial information of written English, the same statistics as cryptographers is employed, looking for the occurrence of specific letters, pairs of letters, triplets of letters and so forth, which is a static analysis independent of global position, and the standard cryptographic technique for cracking a substitution cipher. But Shannon wanted to know how correlated are the letters for people who know the code. That is, a computer can tell us that the letter “q” is highly correlated with a following “u,” but could it, say, determine that this rule is violated for Chinese names? A human could, so Shannon asked them to read texts that had letters removed in order to determine the information encoded in these longer range correlations. In our example, how many letters does it take to decide the word is likely a Chinese name instead of a Latin-root language? Although Shannon worked with written texts, these same rules apply to spoken texts, which make this experiment also a study of time-dependent information content.

Are the spatial and temporal ways of measuring information really independent? A recent paper on the undeciphered pictograms of the Picts, demonstrates their independent character (Lee et al. 2010). The question posed by these carvings was whether they represented a picture, a hieroglyphic/pictogram script, or a syllabic language. Examples of each script type were collected, and the single-symbol frequency statistics (spatial) were plotted on one axis against the statistics of the following symbol (temporal) on the other axis. Each type of communication occupied a distinct cluster on the graph, and the Pictish symbols were adjacent to syllabic languages, suggesting a communication form midway between hieroglyphics and a syllabic language. The key point is that a circular cluster for each communication method, rather than a long ellipse or line, indicates that the two axes are relatively independent so that time and space correlations carry different information.

Applying this to our definition of life, we argue that both spatial and temporal correlations carry information. Not only does the cell exist as a distinct arrangement in space, but this arrangement persists in time, unlike random features seen in clouds or tea leaves. Now in order to avoid prejudicing one type of information over the other, we use Einstein four-vector notation to lump the temporal and spatial components together. Then our generalized Shannon information looks like: $S^\alpha = k\ \ln(\Omega^\alpha)$;

α=(0,1,2,3) with Greek indices carrying the usual meaning of 4-vector space-time where α=0 indicates the time and α=1,2,3 are *x,y,z* spatial components. Note that the information is proportional to the deviation from the diffusion equation, e.g., the magnitude of the negative diffusion coefficient needed to keep the structure from dissipating. Since Boltzmann calculated entropy in units of energy per kelvin, the units on his constant k_0 in this four-vector notation includes the speed of light.

Since S^α is a function of the density of states, and density depends on whether the observer is moving with respect to the particles, we define a relativistic invariant for the information: $I = S^\alpha S_\alpha$ where $k \longrightarrow k'/2$ to keep the normalization.

3.2. FOURIER-SPACE INFORMATION

An analysis of the Shannon information above reveals that it is a local quantity. It depends upon sharp gradients in space, and the maintenance of these gradients in time. But all these descriptions depend on nearest neighbors, they do not incorporate any global knowledge. By these criteria, a vat of beer yeast has no more information than the man who shovels it out. We need a global measure that indicates when diffuse information is correlated.

In Shannon's 1951 paper, he looked at long-range interactions in English words, how a letter two places removed from the missing letter influenced the prediction, or how a letter three places removed influenced it. In standard communication textbooks, these correlations are referred to as 2nd order, 3rd order, etc (Cover and Thomas 1991). We can generalize this long-range correlation as a Fourier transform, where 2nd order terms connect every other point, and 3rd order terms connect every third point etc. It isn't necessary to use sines and cosines as Fourier did, only that there be a transform with a basis set that covers all possible long-range correlations. Then just as nearest neighbors can have information in this density of states, so also non-nearest neighbors can have information in the transform of the density of states.

Note that the zeroth order term in such a transform is just the same local term we described above. Thus the information quantity we are interested in looks something like: $I = S^\alpha S_\alpha + \Sigma_1^L F_i(S^\alpha S_\alpha) = \Sigma_0^L F_i(S^\alpha S_\alpha)$, where $F_i()$ is the transform at some spatial scale *i*, and *L* is the limiting scale size.

Does the information in these various modes add, as we have assumed? From physics, we know that the entropy, *S*, is usually additive for volumes, so the information in different volumes is also additive. We have made a weak argument that information is additive for temporal constancy (a negative diffusion coefficient), which seems odd that something that doesn't change is increasing in information. But the time dimension has different units, and what is important is that the information doesn't disappear at the diffusion speed. Like the Red Queen in Lewis Carroll's masterpiece, it takes energy to maintain homeostasis, and that energy expenditure (divided by temperature) is a negative entropy flow which is information. So the spatial and temporal entropies add.

Do the Fourier components of information add as well? Yes, it would seem natural that they are additive, though the units (inverse space and time) are not the same, nor the magnitudes equal. In Shannon's 1951 work, the information per added letter in an English sentence dropped from some 4.8 bits for the 2nd letter to 1.2 bits for the 10th and following letters like an autocorrelation function, which Shannon estimated by subtracting the information in the (n-1)th letter from the nth letter, making the assumption that the information in the longer correlation lengths was additive.

So if the information in all these different modes is additive, and they all correspond to a logarithm of a density function, then we can create a density function for each mode and multiply these densities together. That is, if the transform of the logarithm is the same as the logarithm of the transform, then this sum can be replaced with a product, $I=k' \ln[\, \Pi^{L}_{0} (\Omega^{\alpha}_{i}\, \Omega_{i\alpha})]$, where i signifies the basis vectors of the transform space.

How much do these higher order terms add to the total information? Generalizing from Shannon's estimate, where the fifth order term drops to one quarter of the zeroeth order term, we estimate that each decade of L contains the same amount of information, giving a power-law dependence of information on scale-size. Then starting at an atomic scale of 10^{-12} m = 1 fm, we would have about 38 decades up to the scale of the universe. This should probably be done for relativistic 4-volumes instead of lengths, so that the information in the Fourier components is about 152 times greater than that in the zeroeth order. If we re-expressed the logarithm as a density of states, then we would say it is equivalent to a very high power of density, $I=k' \ln[\Omega^{\alpha}_{i}\, \Omega_{i\alpha}]^{152}$.

This rather heuristic approach can be physically motivated by considering a series of abiotic chemical steps that can hypothetically make life in a testtube. The reaction, $k_1[a][b] \longrightarrow [c]$, and $k_2\,[c][a] \longrightarrow [d]$ taking place in a single flask, could be written as $k_1 k_2\,[a]^2[b] \longrightarrow [d]$ where the reaction rate or probability is non-linear in [a]. Of course, some reactions may destroy the products much like atmospheric chemistry, so the expected output is found by solving a large matrix of coupled equations. This matrix is just a more accurate physical description of the independent and equal probabilities we had used in our earlier description of searching for arrangements that are "alive." The key difference is that now the different arrangements are not equally probable, nor are they independent. This means we have to abandon our linear approach of adding probabilities, and consider the impact of non-linear terms.

But if we lack the computational resources to find the correct sequence, how does it help if we add in the lack of experimental ability to even produce the correct reaction pathway? It helps because there are potentially both linear and non-linear synthesis pathways, but if a non-linear pathway exists, then under some set of conditions, it will dominate over the linear path. This means that two probabilities collapse down to the one which is more likely. It is a method of improving OOLP, by picking out pairs of probabilities and replacing them with a better single one.

Isn't it even more speculative to talk of non-linear synthesis without evidence? No, because we can examine the end product for examples of duplication, which would be the result of a non-linear input. And duplicates can occur at any size scale, they can be "aa" or "abab" or "aaabbb" and so forth. Finding such items in a data set uses tools like autocorrelation functions which are calculated with Fourier transforms, or fractal analysis over "wavelet" basis vectors. The specific technique is not as important as the concept that information about duplicates and their compression of the linear probabilities can be found in "transform-space." Just as structure can be found locally by taking local gradients, so also duplicates can be found globally by taking "Fourier" components, which appear in the calculation as non-linear exponents on the densities.

4. OOL Detection

What does it mean that there is information in those Fourier components, how does non-local information contribute to micron-sized life? Consider "rogue" waves on the ocean. Most ocean waves are a meter or so high, but occasionally, with no warning, 10, 20 or even 30 meter high waves can topple a ship. Oceanographers suggest that they form spontaneously as the reconstruction of many smaller waves that all arrive in phase. In the same way, each of these Fourier components of information can arrive "in phase" with other information, so as to add up to a greater sum.

Such an interpretation of Fourier components assumes that there can exist "an information wave" that propagates through space. This is precisely what comets represent in the universe, carrying water, carrying chemicals that have been processed by heat and liquid water, carrying genes that are being transported in bacteriophages and cyanobacteria, even carrying entire ecosystems identical to bacterial mats (Hoover 2011). So the OOLP premise is that at some time, $t_0=(t-1)$, no cubic micron in the universe had information content above the threshold, but a "collision" at time t combined the information from two cubic microns to be above the OOL threshold.

Mathematically then, our OOL detector is a large calculation of the four-vector entropy density flow (where the time component is measuring anti-diffusive flow), summed over all Fourier components of interest. When this registers a spike above the threshold, we have the OOL. Then OOLP is found by doing the same calculation summing over the entire universe in space and time for that first spike.

Now the reason for using four-vectors becomes apparent. In order to calculate the best possible number for OOLP, we will need to include all the time between the first star formation (which could then melt comets) and the 3.65 Gyr isotopic identification of life on Earth. Using Einstein's block universe with time being just another dimension like the other three spatial dimensions, we can calculate OOLP as a four-vector information over the expanding universe for those 8 Gyr. As we described before, this additional volume and time barely changes the linear probabilities, adding a mere 24 zeroes to OOLP, but it does add information in the Fourier components, raised to the 152 power. So a power-law in scale length provides a modest increase in the Shannon information exhibited, though not enough to change our OOLP calculation by very much. However it does indicate a way in which comets can contribute non-linear information to OOLP.

4.1. THE COMET ADVANTAGE

How does this "comet information wave" model differ from Darwin's warm pond? Darwin had all his chemicals in solution, a high-entropy and low-information situation, whereas comets keep all their chemicals locked in a deep freeze until the last moment (near perihelion), which is a low-entropy high-information system. Darwin added sunlight and heat to his pond to provide the energy for life, a high entropy energy source, whereas comets provide inhomogeneous chemicals, often lingering at the melting point of ice, a low entropy energy source. One way to characterize the suitability of energy sources for work is by calculating the Gibbs free energy or exergy, $G=H - TS$, where H is the enthalpy and T the temperature. Since G is proportional to negative temperature, life prefers it cool, which is why trees evaporate 99% of the water they take in at their roots, a feat consuming 66% of sunlight energy, just to increase their exergy by cooling their leaves (Schneider and Sagan 2005). Since comets linger near the melting point of water as they melt, they have the maximum exergy possible.

But most importantly, Darwin had no way for warm ponds to communicate. All the information had to be available locally, there was no method of communicating information, collecting information, or distributing it. Comets provide a mechanism for all these things, and in so doing, provide the network that permits Fourier space to influence real space, because Fourier space does more than communicate information, it also stores it. Another example demonstrates the importance of distributed information within a network.

Because the human brain has proportionately the same density of neurons as any other primate (Herculano-Houzel 2009), it would seem that only brain size matters for intelligence. But most brain researchers argue that it is not size but the number of cross-connects that make the human brain so versatile. The information lies not in the number of nodes, (spatial complexity) but in the number of dendrites, the number of cross-connects (Fourier complexity). The 30 billion cells of the human brain, with its 10,000 cross-connects possesses about 10^{15} synapses. But many of those synapses form loops, which may be important to memory, so intelligence likely scales non-linearly as well, to some power in synapse number.

This non-linear behavior is a consequence not just of the connections between neurons, but of order in which connections are made. This means we count permutations ($n!$) rather than combinations of synapses ($\sim n$), where the number of states or the information bits per synapse, is an exponentially growing function of synapse number, just as in a maximally entangled coherent quantum state (Abrams and Lloyd 1999). That is, instead of 10^{15} bits, we have perhaps 10 to the power 10^{15} bits per brain, all because of the coherency of the cross-connects (Linde and Vanchurin 2010).

Therefore comets may provide a distributed but connected web of information flow in the solar system, in the galaxy and possibly in the universe. This would permit the information content of the whole to be greater than the linear sum of the parts. In our terminology, this permits the Fourier-space information to dominate over the local and linear information content. By analogy to the problem of the entire universe having only about 10^{120} computational bits, we have achieved much greater computational resources of the universe by replacing the serial computation of a (local) silicon chip with the parallel processing of a quantum (non-local) computer. It is precisely because a quantum computer incorporates entanglement between bits, the non-local and non-linear correlations, that it outperforms local linear silicon-based computers (Shor 1995).

But can even Fourier space provide enough information processing? Supposing the entire universe were a computer, with its 120 decades of information, we would need a non-linearity of the 10th power to get it up to 1200 decades for a moderately complex molecule, and non-linearities of 100th or 1000th power to achieve a minimal life form. If simple loops produce a quadratic power, then how many “cross-connects” are needed to get 10th power or 100th power? Isn’t that asking a lot from comets?

It is. Especially because the number of comets in the galaxy is not expected to be more than 10^{21}, or in the universe, 10^{31}. Collisions or cross-connects between comets are not expected to be more than 10, so we are not really asking comets to provide the information storage and processing, only the distributed information network which connects information rich regions. Once again, comets are macroscopic objects with some 10^{39} water molecules, so they stand, logarithmically, about half-way between atoms and the universe in scale-size. Their purpose, then, is to provide the mechanism that connects information at the large scales of galaxies and stars with the information at the small scales of cells and organisms. Without them, the Fourier space of large scales would be devoid of information, or at best, there would be no information flow between the smallest and largest spatial scales. Comparing the lost connections, we have the Earth being a volume of about one part in 10^{59} of the universe, which logarithmically is roughly double the one part in 10^{32} for the ratio of a microbe to the volume of the Earth. Therefore comets open up 200% more log-space volume for Fourier components.

That is, comets provide a mechanism to connect the universe of Darwin's warm ponds together, so as to provide a unified information system greater than the linear sum of the parts. Comets, in addition to their linear importance in adding to the total number of Darwinian ponds, also provide the non-linear Fourier space information that connects information rich regions together, both at larger and at smaller scales. Without this connection, the Fourier series would truncate early, unable to connect the information on one planet with another, much less the information from the whole galaxy.

4.2. COMETARY ABUNDANCES

The claim that comets connect large with small spatial scales should be elaborated, lest we fall back into the panspermia idea that comets merely transport microbes from one world to another, without providing an information source of their own (e.g., Arrhenius 1908). We distinguish our model where comets are an integrating complex information system necessary for OOL from the linear panspermia model by calling ours panzooia, where the prefix "pan" refers to its non-locality, and the root "zooia" refers to all life (Sheldon and Hoover 2007).

Astronomical measurements of the motion of the stars in the Andromeda galaxy reveal that they are orbiting the center, but with non-Keplerian speeds of the sort found for planetary orbits around the sun. Rather, the stars seem to orbit as a rigid body, as if they are embedded in an invisible sphere (Volders and van de Hulst 1959;

Rubin and Ford 1970). The distribution of matter that permits such motion is proportional to distance from the center of the galaxy, such that the "funnel shaped" gravitational potential of a stellar source of matter is broadened into a flattened well, usually attributed to "dark matter," or massive material that cannot be seen with astronomical telescopes. These stellar rotation curves do not require modifications to Newtonian gravity, or invocation of non-baryonic matter (e.g., heavy neutrinos), they merely require a radially dependent star/mass ratio, where the galaxy becomes progressively more "dusty" with radius (Gallo and Feng 2010). Since high stellar densities "heat" a cometary velocity through gravitational slingshots and jetting of gases on the comet, one expects this radial profile for cometary density in galaxies if the cometary kinetic and potential and starlight energy are "virialized" to the same $1/r^2$ dependence.

We refer to "dusty" as indicative of dark matter that has not yet been observed by telescope. If it were actual micron dust grains, we could observe them in the infrared frequency range. If it were neutral hydrogen, we could observe them in the radio, or if heated, in the UV range. If it were compact objects–black holes, neutron stars, brown dwarfs–we could observe their gravitational microlensing or their occultation of background stars. As it is, we only detect them from large-scale gravitational effects of changing the rotation curves of galaxies, or at the galaxy-wide level, lensing the background galaxies. Therefore we are looking for dark matter that is neither too finely divided that it extinguishes light, nor too highly clumped that it can be seen gravitationally; it has neither a large photon cross section, nor a large gravitational cross section. This means it has to be larger than a sand grain, but smaller than a Jupiter. Comets fit that description.

The best support for large numbers of galactic comets comes from observations of the "bullet cluster" of colliding galaxies. The collision produced a distinct shock wave in the heated hydrogen gas clouds, and a perceptible offset between the bright stellar center-of-mass and the gravitational lensing center-of-mass. With sophisticated modeling, the "dark matter" ratio of cross-sectional area to mass can be computed from this data (Randall et al. 2008). An upper limit puts the ratio at 0.7 cm^2/g. If we calculate this ratio for comets, and assuming a spherical comet of radius r, we have mass $m=4/3\pi r^3\rho$, and the cross-sectional area, $A=\pi r^2$, giving a ratio, $A/m=3/(4r\rho)$. Plugging in a typical comet density of 0.5 g/cm^3 , we get $r{\sim}2$ cm or about 32 g. This is a bit small for solar system comets, which tend to have radii about 2000 m, or 10^5 larger than this. However the bullet cluster merely sets an upper limit, and the smaller this ratio, the better it fits the comet model. It also illustrates very nicely the interpolation of cross-sections between gas with radii 10^{-9} m and brown dwarfs with radii $\sim 10^8$ m.

There is one other objection to galactic comets fulfilling the role of "dark matter," and that is the assertion that 70% of the matter in the bullet cluster or in the universe is "dark" (Clowe et al. 2006; Angus et al. 2007). This would make comets and their associated carbon and oxygen more abundant than stars and their constituent hydrogen and helium, which would violate the 75:25:0.01 mass ratio of cosmological hydrogen:helium:metals production in the Big Bang Nucleosynthesis (BBN) models. This is a serious problem for our galactic comet hypothesis, which can be resolved by either (a) following the current paradigm where 90% or more of dark matter is non-baryonic with small admixtures of comets consistent with Solar System abundances; (b) positing some early stage of galactic formation that burns H and He to C and O, which later form comets (Gibson, Wickramasinghe, and Schild. 2010); or (c) arguing that BBN models have not properly taken into account the "plasma" age of the universe, between nucleosynthesis and neutralization of atoms.

Our preference is (c), for if strong Big Bang magnetic fields exist, then magnetized plasma modes can provide degrees of freedom not available to the hot-gas models of BBN, prolonging the ~20 minute era of giga-Kelvin temperatures, and providing non-thermal channels for nucleosynthesis to continue. This may have changed the H:He:C:O ratios, whereupon later condensation into comets would have "hidden" the CO from spectroscopic discovery, since C and O are both "sticky" elements, likely to form interstellar solids that are not easily detected spectroscopically. Furthermore, their volatility in the proto-solar nebula would have caused them to migrate anti-sunward during the accretion phase, so that they are underrepresented in stellar composition, and hence in spectroscopic observations of stars. In a now-discredited theory, Frank argues for the ubiquity of meter-sized comets in the solar-system, making many of the same sort of "invisibility" arguments for "cometesimals" (Frank et al. 1986; Frank 1990). Nevertheless, we find this baryon-density argument to be a formidable objection, requiring a comprehensive plasma-BBN model to address this issue quantitatively.

4.3. COMET LOOPS

Making the assumption that comets are not just ubiquitous but numerous in the early universe, we can now see how they can connect the large and small scales of the universe. Since the atoms of C, O, or their simple hydrogenized forms–CH_4, H_2O, CO and CO_2–are all easily condensed, they would nucleate much sooner than the giant hydrogen and helium clouds. As a consequence, gas clouds in the early universe would go unstable to accelerated gravitational collapse much sooner, and provide the superstructure of galactic clusters and voids observed today, as is provided by "dark matter" in all the cosmological models.

Galaxy clusters, such as the Coma supercluster, must form before the galaxy begins stellar formation, they require a dark matter seed (Zwicky 1937), which can be provided by comets since they are the first to condense out of the proto-galactic nebula. The same is true at the smaller sub-galactic scale of globular clusters, whose stars are generally much older than the galactic disk. Since globular clusters have higher average stellar velocities than galaxies, and cluster galaxies higher than field galaxies, we would expect these clusters to evaporate comets with much higher relative velocities, enabling these high-speed comets to seed neighboring galactic nebulae. This self-seeding or catalytic character of comets is similar to diffusion limited growth, and may account for some of the cosmic galactic structure such as "the great wall" which is presently attributed to unspecified "dark matter."

As stellar formation began in proto-galaxies, the immediate heat flux would drive the comets away, due to gas jetting on the surfaces of comets. Thus comets have a built-in repulsion for stars, which we may be observing in the galactic rotation curves discussed earlier. The greater the repulsion, the more likely that comets will "evaporate" from galaxies, and not contribute to star formation. Not coincidently, this "repulsive force" depends on the spectral reflectivity of comets, and the big surprise in the past 25 years was the discovery that "old" comets are blacker than carbon soot. This makes them maximally sensitive to thermal radiation, and may be a consequence of cyanobacterial biofilms forming on the outside of the comet (Sheldon and Hoover 2006, 2007). That is, the spectral characteristic of comets that makes them more efficient galactic messengers is itself a consequence of life.

Therefore just as Gaia theory argues that Earth climate is stabilized by life, so it may be possible that galaxy formation was itself catalyzed by life, making this universe with all its anthropic contingency merely a consequence of biological homeostasis. Whether this corollary hypothesis bears up or not, we present it as an example of how the largest scales observed in cosmology can be connected to the smallest scales of biology through the mediation of comets.

We began this discussion on comets by describing them as the messengers of the universe, much like the neurons in the brain, connecting the spacetime pixels of static spatial information to produce dynamic information, populating the matrix of Fourier transform information. We ended by arguing that life could modulate galaxy formation in such a way as to make the universe hospitable for advanced life, a combination of Strong Anthropic Principle and Gaia Hypothesis (Carter 1974; Lovelock and Margulis 1974). But perhaps a better way to view this emphasis on Fourier space information is to recognize that the macrocosm mirrors the microcosm, that the universe bears more than passing resemblance to the cell, with comets providing an analog of the tubulin proteins that give shape and structure to the cell and are the highways for non-diffusive information transport. Thus science may recover the medieval golden chain of being that connects the earth and the heavens (Lewis 1964).

5. Discussion and Conclusion

The OOL problem arose in the 19th century when materialism replaced theism as the metaphysics of science. (Some might argue that science is defined by its materialist metaphysics, and therefore deny the existence of science until the Enlightenment, but this narrow definition does disservice to the contributions of Aristotle, Archimedes, and the countless “giants” on whose shoulders Newton stood.) In this more restricted scientific metaphysics, Aristotle’s material causes trump his final causes, and life is to be described by “how” rather than “why.” With the discovery by Pasteur that spontaneous generation is highly unlikely, and with the 20th century advances in biochemistry that made spontaneous generation impossible in a finite universe (Meyer 2009), the OOL problem crystallized all the metaphysical objections to materialism that had been raised by Aristotle and subsequent generations of philosophers.

Elsewhere in 20th century science, materialism posed less of an impediment, and progress was made in information theory, astronomy and cosmology that led to several important discoveries of conservation laws. The late 1800s saw the development of thermodynamics, and its twin concepts of energy conservation and entropy growth, despite neither being a material property of matter envisioned by Democritus. Thermodynamics was brought back into the fold of materialism by Boltzmann, who gave it a particle (statistical mechanics) interpretation, and along the way defined entropy as a probabilistic ordering of these particles. A half-century later, Shannon laid the foundation of the computer revolution by demonstrating how the flip side of entropy is information, and by showing how machines can process that information digitally.

The implications from Shannon’s new field of Information Theory rippled outward into all of the sciences, especially physics. Quantum mechanics reported experiments whose outcome depended purely on information (e.g., Kim et al. 2000). Hawking began to consider the effects of entropy and energy on astrophysics, concluding that entropy (and therefore information) is conserved even as black holes devour the matter of materialism (Hawking 2005; Susskind 2008), so in some sense, the immaterial information is more permanent than the material matter. This progress toward immaterialism is no more evident than in the career of the late physicist John Wheeler, who described his life as composed of three phases: "Everything is Particles; Everything is Fields, and Everything is Information." His memorable aphorism to describe this final phase was "It from Bit" (Wheeler and Ford 1999)–existence comes from information—which is the exact opposite of the materialist-inspired aphorism of the mid-20th century "existence precedes essence" (Sartre 1943). For the first time since Aquinas, scientists are now seriously considering not just the inadequacy of materialism, but the prior necessity of immaterialism.

This shift may explain the 2010 publication of a curious paper by Verlinde, in which he argues that conservation of energy and conservation of information, with some mathematical machinery of 4-D spacetime, can not only reproduce Einstein's general theory of relativity, but also Newton's laws of motion (Verlinde 2010). That is, the materialist assumptions of point particles travelling through the void which were so ably quantified by Newton's calculus, have now been derived, not assumed, from conservation laws of energy and information. Two completely immaterial concepts have been combined so as to derive the material. Materialism is not the basis of science, but a corollary of science.

This information, including that in the Fourier realm which we argue is necessary to explain the origin of life, is now thought by many to be a permanent feature of the universe, which from a physics standpoint, means a contingent feature of the Big Bang. The Anthropic Principle, which paled at the prospect of a finely tuned explosion to one part in 10^{60} such that one grain of sand more or less would have made the universe devoid of life, must now contend with contingent information of far greater magnitudes.

This conservation of information from the Big Bang is often misunderstood as "front-loading," or as the British Deists described it, as the winding up of a watch (Paley 1809). This description is inadequate if time is treated as a separate dimension as in, for example, a wound-up watch with a spatial arrangement of springs and levers that deterministically evolve in time; a boundary condition in space that sets x_0 and v_0 and then follows $F=ma$ in time. Free choice seems to be missing from the equation, and likewise, entropy appears to be growing as the spring gets hot, destroying information. However, the watch in four-dimensional spacetime not only has a boundary condition in space, but a boundary condition in time. Thus information is continually propagating to the watch from that temporal boundary condition as it unwinds, just as information is imparted to the watch from its spatial boundary condition as it unwinds. That information may include, for example, instructions to rewind the watch. These information flows in spacetime mean that the system is not "closed" to outside influence, which would then lead to entropic information loss, but capable of becoming more complex.

Applying this to our OOL problem, the appearance of life is not explained as an internal law of complexification (aka, vitalism), or an internal production of information (aka materialist evolution), but as a consequence of external information flow (e.g., comets), bringing information from the 4D spacetime boundary condition that accompanied the Big Bang (Sheldon and Hoover 2008).

What would this OOL scenario look like to an observer within the system? Making an analogy to Paley's watch, we can imagine labeling all the atoms of the watch, and then running the movie back one year to see how that watch came to be. We would see tagged atoms of copper and tin and zinc coming from ores, being purified and concentrated, melted and mixed and shaped and cut and polished. Then from locations all over the Earth, these components would arrive and concentrate into subassemblies, which further transport would bring to the watch factory and suddenly they would all assemble and the watch would begin to function. Distributed information is displayed by the sequencing of these events, where at each moment of the movie, information is being added in the form of concentrating, shaping and structuring, and where at no point in the movie would there be an entropic or information destroying event.

In the same way, the movie of OOL might show a highly diffuse and distributed information system that concentrated, altered and structured the organic molecules. Not only would OOL involve more than a warm pond on the Earth, it would likely involve more than all the warm ponds in the Solar System and galaxy. As the universe expands and as the galaxies contract, the necessary information would likely concentrate, moving from the 4D boundary of the Big Bang toward the middle, toward a spacetime volume perhaps on a comet, where a living organism could then appear. How does this miracle occur? By adding slightly less information rich systems together in improbable, but not wildly improbable steps, until the OOL threshold is crossed.

In conclusion, we have attempted to show that the OOL problem runs aground on the metaphysical shoals of materialism and its assumption of incoherence. Information theory provides a way forward, but must be expanded to include non-local, or Fourier space information to accommodate the vast amounts of information encoded by life. This required capacity, when generalized to Einstein's spacetime, is claimed to be a conserved quantity of the universe that must also incorporate time, which makes information flow a necessary consequence of information capacity. When combined with the conservation laws, this information flow is from the 4D boundary conditions of the Big Bang inward, toward the volume that includes the Earth. Materially, we find that comets have all the properties to mediate this information flow, and the cometary hydrosphere can therefore be the physical realization of this mathematical necessity. We provide some weak justification for singling out comets for this monumental task, incidentally suggesting that they may also provide the solution to the missing "dark matter" problem.

When we examine the solution we have derived, we find that it has led several prominent physicists to propose the priority of information and the derivative nature of materialism. Thus the OOL problem may be solved by turning materialism on its head. Rather than finding life to be a difficult accomplishment for a materialist, we find instead that materialism may be a trivial accomplishment for life.

6. References

Abrams, D. S., and S. Lloyd, Quantum Algorithm Providing Exponential Speed Increase for Finding Eigenvalues and Eigenvectors, *Physical Review Letters*, *83*, 5162–5165, doi:10.1103/PhysRevLett.83.5162, 1999.

Angus, G. W., H. Y. Shan, H. S. Zhao, and B. Famaey, On the Proof of Dark Matter, the Law of Gravity, and the Mass of Neutrinos, *Astrophys. J. Lett.*, *654*, L13–L16, doi:10.1086/510738, 2007.

Arrhenius, S., *Worlds in the Making: The Evolution of the Universe*. New York, Harper & Row, 1908.

Axe, D. D., Estimating the prevalence of protein sequences adopting functional enzyme folds, *Journal of Molecular Biology*, *341*, 1295–1315, 2004.

Barrick, J. E., D. S. Yu, S. H. Yoon, H. Jeong, T. K. Oh, D. Schneider, R. E. Lenski, and J. F. Kim, Genome evolution and adaptation in a long-term experiment with escherichia coli, *Nature*, *461*, 1243–1247, 2009.

Carter, B., Large number coincidences and the anthropic principle in cosmology, in *IAU Symposium 63: Confrontation of Cosmological Theories with Observational Data*, pp. 291-298, Reidel, Dordrecht, 1974.

Clowe, D., M. Bradač, A. H. Gonzalez, M. Markevitch, S. W. Randall, C. Jones, and D. Zaritsky, A Direct Empirical Proof of the Existence of Dark Matter, *Astrophys. J. Lett.*, *648*, L109–L113, doi:10.1086/508162, 2006.

Coates, A. J., G. H. Jones, G. R. Lewis, A. Wellbrock, D. T. Young, F. J. Crary, R. E. Johnson, T. A. Cassidy, and T. W. Hill, Negative ions in the Enceladus plume, *Icarus*, *206*, 618–622, 2010.

Cover, T. M., and J. A. Thomas, *Elements of Information Theory*, John Wiley and Sons Inc, New York, NY, 1991.

Davies, P., *The Fifth Miracle: The Search for the Origin and Meaning of Life*, Simon & Schuster, New York, 2000.

Darwin, C., *On The Origin of Species by Means of Natural Selection, or The Preservation of Favoured Races in the Struggle for Life*, John Murray, London, 1859.

Darwin, F., *The life and letters of Charles Darwin, including an autobiographical chapter*, vol. 3, 18 pp., John Murray, London, 1887.

Dawkins, R. *The Blind Watchmaker* , Oxford University Press: Oxford, 1986.

Dembski, W., *The Design Inference: Eliminating Chance Through Small Probabilities*, Cambridge: Cambridge University Press, 1998.

Dembski, W., *No free lunch: Why specified complexity cannot be purchased without intelligence*, Rowman and Littlefield Pub. Inc., Lanham, MD, 2002.

Dembski, W., and R. J. Marks II, The search for a search: Measuring the information cost of higher level search, *Journal of Advanced Computational Intelligence and Intelligent Informatics*, *14*(5), 475–486, 2010.

Farley, J., *The Spontaneous Generation Controversy from Descartes to Oparin*, Johns Hopkins University Press, Baltimore MD, 1974.

Frank, L. A., *The Big Splash: A Scientific Discovery That Revolutionizes the Way We View the Origin of Life, the Water We Drink, the Death of the Dinosaurs,...*, Birch Lane Press, New York, 1990.

Frank, L. A., J. B. Sigwarth, and J. D. Craven, On the influx of small comets into the earth's upper atmosphere. I - Observations. II - Interpretation, *Geophys. Res. Lett.*, *13*, 303–310, doi:10.1029/GL013i004p00303, 1986.

Gallo, C. F., and J. Q. Feng, Galactic rotation discribed by a thin-disk gravitational model without dark matter, *Journal of Cosmology*, *6*, 1373–1380, 2010.

Gibson, C. H., N. C. Wickramasinghe, and R. E. Schild, First life in primordial-planet oceans: the biological big bang, *ArXiv e-prints*, 2010.

Gibson, D. G., J. I. Glass, C. Lartigue, V. N. Noskov, R.-Y. Chuang, M. A. Algire, G. A. Benders, M. G. Montague, L. Ma, M. M. Moodie, C. Merryman, S. Vashee, R. Krishnakumar, N. Assad-Garcia, C. Andrews-Pfannkoch, E. A. Denisova, L. Young, Z.-Q. Qi, T. H. Segall-Shapiro, C. H. Calvey, P. P. Parmar, C. A. Hutchison III, H. O. Smith, and J. C. Venter. Creation of a bacterial cell controlled by a chemically synthesized genome, *Science*, *329*(5987), 52–56, 2010.

Gödel, K., "Über formal unentscheidbare Sätze der Principia Mathematica und verwandter Systeme, I." Monatshefte für Mathematik und Physik 38: 173-98, 1931.

Guth, A. H., Eternal inflation and its implications, *Journal of Physics A Mathematical General*, *40*, 6811–6826, doi:10.1088/1751-8113/40/25/S25, 2007.

Hawking, S. W., Information loss in black holes, *PhysRevD*, *72*(8), 084, 013, doi:10.1103/ PhysRevD.72.084013, 2005.

Herculano-Houzel, S., The human brain in numbers: a linearly scaled-up primate brain, *Front Hum Neurosci.*, *3*, 31, 2009.

Hoover, R. B., Comets, carbonaceous meteorites, and the origin of the biosphere, in *Biosphere Origin and Evolution*, edited by N. Dobretsov, N. Kolchanov, A. Rozanov, and G. Zavarzin, pp. 55–68, Springer US, 2008.

Hoover, R. B., E. V. Pikuta, N. C. Wickramasinghe, M. K. Wallis, and R. B. Sheldon, Astrobiology of comets, in *Instruments, Methods, and Missions for Astrobiology VII*, edited by R. B. Hoover, G. V. Levin, and A. Y. Rozanov, pp. 93–106, Proc. of SPIE Vol 5555, Bellingham, WA, 2004.

Hoover, R. "Fossils of Cyanobacteria in CI1 Carbonaceous Meteorites", *J. Cosmology*, *13*, 1+, March, 2011.

Hoyle, F. and C. Wickramasinghe, In *Comets and the Origin of Life*, ed. C. Ponnamperuma, D. Reidel Publishing Co., Dordrecht, p.227, 1980.

Hoyle, F, and C. Wickramasinghe,, *Evolution from Space*, J.M. Dent, London, 1981a.

Hoyle, F. and C. Wickramasinghe, *Proofs that Life is Cosmic*, Mem. Institute of Fundamental Studies, Sri Lanka, No. 1, http://www.panspermia.org/proofslifeiscosmic.pdf, 1981b.

Hoyle, F., *The Mathematics of Evolution*, Acorn Enterprises, Memphis, TN, 1999.

Hoyle, F. and C. Wickramasinghe, *Astronomical Origins of Life*, Kluwer Academic Pub, Dordrecht, 2000.

Kim, Y.-H., R. Yu, S. P. Kulik, Y. Shih, and M. O. Scully, Delayed 'choice' quantum eraser, *Phys. Rev. Lett.*, *84*(1), 1–5, doi:10.1103/PhysRevLett.84.1, 2000.

Komatsu, E., et al., Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Interpretation, *Astrophys. J. Suppl. 192*:17, doi:10.1088/0067-0049/192/2/17, 2011.

Lee, R., P. Jonathan, and P. Ziman, Pictish symbols revealed as a written language through application of Shannon entropy, *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science*, *466*(2121), 2545–2560, doi:10.1098/rspa.2010.0041, 2010.

Levin, G. V., and P. A. Straat, Viking labeled release biology experiment - interim results, *Science*, *194*, 1322–1329, 1976.

Lewis, C. S., *The Discarded Image: An Introduction to Medieval and Renaissance Literature*, Cambridge University Press, Cambridge, 1964.

Linde, A., and V. Vanchurin, How many universes are in the multiverse?, *PhysRevD*, *81*(8), 083,525–+, doi:10.1103/PhysRevD.81.083525, 2010.

Lloyd, S., Computational capacity of the universe, *Phys. Rev. Lett.*, *88*(23), 237,901, doi:10.1103/PhysRevLett.88.237901, 2002.

Lovelock, J. E., and L. Margulis, Atmospheric homeostasis by and for the biosphere: The gaia hypothesis, *Tellus*, *26*, 2, 1974.

Lucretius Carus, T., *Of the Nature of Things (De Rerum Natura)*, E. P. Dutton and Co. Inc., New York, 1921.

Meyer, S. C., *Signature in the Cell: DNA and the Evidence for Intelligent Design*, HarperCollins Pub., New York, NY, 2009.

Mojzsis, S. J., T. M. Harrison, and C. E. Manning, The oldest known sediments on Earth: Implications for exobiology, *Geochimica et Cosmochimica Acta Supplement*, *67*, 300, 2003.

NASA/Jet Propulsion Laboratory, Life on Titan? New Clues to What's Consuming Hydrogen, Acetylene on Saturn's Moon, *ScienceDaily*. Retrieved January 5, 2012, from http://www.sciencedaily.com /releases/2010/06/100606103125.htm

Oak Ridge National Laboratory, "Oak Ridge 'Jaguar' Supercomputer Is World's Fastest," *ScienceDaily*. Retrieved January 5, 2012, from http://www.sciencedaily.com /releases/2009/11/091116204229.htm

Paley, W., *Natural Theology: or, Evidences of the Existence and Attributes of the Deity*, 12 ed., J. Faulder, London, 1809.

Pasteur, L., Mémoire sur les corpuscules organisés qui existent dans l'atmosphère. Examen de la doctrine des générations spontanées, *Ann. sci. naturelles (partie zoologique) (Sér. 4)*, *16*, 5–98, 1861.

Peret, J., J. Bada, and A. Lazcano, Charles Darwin and the origin of life, *Origins of Life and Evolution of Biospheres*, *39*, 395–406, 10.1007/s11084-009-9172-7, 2009.

Pitts, J. B., Gauge-Invariant Localization of Infinitely Many Gravitational Energies from all Possible Auxiliary Structures, *General Relativity and Gravitation*, *42*, 601-610, doi:10.1007/s10714-009-0874-y, 2010.

Polanyi, M., Life's Irreducible Structure, *Science*, *160*, 1308–1312, 1968.

Randall, S. W., M. Markevitch, D. Clowe, A. H. Gonzalez, and M. Bradač, Constraints on the Self-Interaction Cross Section of Dark Matter from Numerical Simulations of the Merging Galaxy Cluster 1E 0657-56, *Astrophys. J.*, *679*, 1173–1180, doi:10.1086/587859, 2008.

Rubin, V. C., and W. K. Ford, Jr., Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions, *Astrophys. J.*, *159*, 379, doi:10.1086/150317, 1970.

Sartre, J.-P., *L'Être Et Le Neant*, Gallimard, Paris, 1943.

Schneider, E. D., and D. Sagan, *Into the Cool: Energy Flow, Thermodynamics, and Life*, University of Chicago Press, Chicago, 2005.

Shannon, C. E., A mathematical theory of communication, *Bell System Technical Journal*, *27*, 379–423,623–656, 1948.

Shannon, C. E., Prediction and entropy in written English, in *Claude Shannon collected papers*, edited by W. A. D. Sloane N. J. A., p. 583, IEEE Press, Piscataway, NJ, 1993.

Shannon, C. E., and W. Weaver, *The mathematical theory of communication*, University of Illinois Press, Urbana, 1949.

Sheldon, R. B., and R. B. Hoover, Evidence for liquid water on comets, in *Instruments, Methods, and Missions for Astrobiology VIII*, edited by R. B. Hoover, G. V. Levin, and A. Y. Rozanov, pp. 196–206, Proc. of SPIE Vol 5906A, Bellingham, WA, 2005.

Sheldon, R. B., and R. B. Hoover, Implications of cometary water: Deep impact, stardust and hayabusa, in *Instruments, Methods, and Missions for Astrobiology IX*, edited by R. B. Hoover, G. V. Levin, and A. Y. Rozanov, pp. 6309–0L, Proc. of SPIE Vol 6309, Bellingham, WA, 2006.

Sheldon, R. B., and R. B. Hoover, The cometary biosphere, in *Instruments, Methods, and Missions for Astrobiology X*, edited by R. B. Hoover, G. V. Levin, and A. Y. Rozanov, pp. 6694–0H, Proc. of SPIE Vol 6694, Bellingham, WA, 2007.

Sheldon, R. B., and R. B. Hoover, Cosmological evolution: Spatial relativity and the speed of life, in *Instruments, Methods, and Missions for Astrobiology XI*, edited by R. B. Hoover, G. V. Levin, and A. Y. Rozanov, pp. 7097–41, Proc. of SPIE Vol 7097, Bellingham, WA, 2008.

Shor, P. W., Quantum Computers, Factoring, and Decoherence, *Science*, *270*, 1633-1635, 1995.

Strobel, D. F., Molecular hydrogen in Titan's atmosphere: Implications of the measured tropospheric and thermospheric mole fractions, *Icarus*, *208*, 878–886, doi:10.1016/j.icarus.2010.03.003, 2010.

Susskind, L., *The anthropic landscape of string theory*, pp. 247–+, Cambridge University Press, Cambridge, 2007.

Susskind, L., *The Black Hole War: My Battle with Stephen Hawking to Make the World Safe for Quantum Mechanics*, Little, Brown, & Co., New York, 2008.

Verlinde, E. P., On the Origin of Gravity and the Laws of Newton, *J. of High Energy Physics*, *4*, 29+, 2010.

Volders, L., and H. C. van de Hulst, Neutral hydrogen in extra-galactic systems, in *URSI Symp. 1: Paris Symposium on Radio Astronomy*, *IAU Symposium*, Vol. 9, edited by R. N. Bracewell, pp. 423–430, Stanford University Press, Stanford, CA, 1959.

Wheeler, J. A., and K. W. Ford, *Geons, Black Holes, and Quantum Foam: A Life in Physics*, Norton, New York, NY, 1999.

Wickramasinghe, N. C., M. Wainwright, J. V. Narlikar, P. Rajaratnam, M. J. Harris, and D. Lloyd, Progress towards the vindication of panspermia, *Astrophysics and Space Science*, *283*, 403–413, doi:10.1023/A:1021677122937, 2003.

Wickramasinghe, C., Viva Panspermia, *The Observatory*, *131*, 130-134, June, 2011.

Zwicky, F., On the Masses of Nebulae and of Clusters of Nebulae, *Astrophys. J.*, *86*, 217, doi:10.1086/143864, 1937.