"The search for extra-terrestrial life is a failure until that moment when it suddenly becomes a success." Shostak (2008)

1. INTRODUCTION

Cosmic Pluralism, the notion that the universe contains many worlds of intelligent inhabitants, has been discussed for millennia (Darlingweb1) and more recently, the post war economic expansion from 1945 to 1975 saw huge investment in military/space programs (Aerospaceweb) as well as rapid development of social libertarianism (Boaz 2009). These two cultural threads overlapped in the northern summer of 1950 (Konopinsky 1985) when, at the Los Alamos National Laboratory in New Mexico, a clique of physicists were on their way to lunch (PhysOrgweb). They were chatting about the so-called UFO sightings reported in the local media, when Prof. Fermi asked "Where is everybody?". This paradox, later branded the Great Silence (Brin 1983), is a label that has stuck to Enrico Fermi, Italian Nobel physics laureate of 1938. However, peer reviewed discussion of the lack of aliens on Earth didn't begin until the mid 70s (see Hart 1975), and it paralleled the simmering UFO/conspiracy theories of the day.

UFO sightings in the USA surged from 1947, after a reported crash landing near the town of Roswell, New Mexico (Project1947web). The official response from the USAF was that a test balloon had crashed on an outlying ranch (Highbeamweb). This started a runaway conspiracy theory, the flames of which were fanned by UFOlogists, and later re-visited by media such as the National Enquirer newspaper (Skepdicweb). A meme was born. A meme that has consumed many people since.

With the rapid development of modern technology, interplanetary exploration and the discovery of terrestrial extremophiles, the existence of intelligent extra-terrestrials (ETI) is now a legitimate discussion in modern science. Notwithstanding the Kardashev Scale where civilisation is classified into Phase I, II, or III depending on their harness of planetary, solar, then galactic energy, (Kardashev 1964), a discussion about Fermi's Paradox is usefully constrained to extra-terrestrial beings who have sufficient technology to communicate 'in person', digitally or by space probe, across interstellar space. According to Dr Herbert York, a participant in the original Los Alamos discussion, Fermi subsequently derived numbers for some variables of the idea, and concluded that technologically intelligent aliens from within the Galaxy, should already have visited Earth (PhyOrgweb). It has since been suggested that it should only take 10^8 years for a civilization to expand across the entire Galaxy (Tipler, 1981).

By the late 1950s, radio astronomers were sufficiently motivated to suggest searching for extra-terrestrial signals via the 21 cm Hydrogen signal – an anticipated universally recognised part of the electromagnetic spectrum (Cocconi & Morrison 1959). By this time, respected astronomy Prof. Harlow Shapley had measured the size of the Galaxy, postulated a "Habitable Zone" around stars, suggested aliens could live on Brown Dwarfs and reasoned that by pure weight of numbers, aliens will "*…emerge, persist and evolve…*" on many planets (Darling & Schulze-Makuch 2016).

The first efforts to detect extra-terrestrial radio signals were made by Dr Frank Drake in 1960 during Project Ozma (SETIweb1). A year later, Drake participated in a meeting of the Space Science Board at the National Radio Astronomy Observatory in Green Bank, West Virginia. The discussion was around an equation Drake had derived, that related the components needed to calculate the number of Galactic civilizations with which we could communicate (Darlingweb2). The equation is presented in Fig. 1 and will be discussed in some depth later in this essay.

Reasonably, parts of the Drake Equation are of specific interest to astrobiologists, and so drive the purpose for this essay. One consequent thread discussed by scientists, is the likelihood of an inherent 'halting' phase in the evolution of intelligent life that prevents it arising at all, or at least severely restricts it - perhaps to just one incidence (AstroMagweb, Lineweaver et al 2004, Chopra & Lineweaver 2016, Bradshaw & Brook 2009, GMUweb, Ward 2015). These halting phases are usually called filters or bottlenecks in the literature, and variously postulate an acute event, or a set of biochemical, planetary and/or cosmological circumstances that address terms 5 and/or 6 in the Drake Equation.

$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$

N	Present number of extraterrestrial races capable of interstellar communication
R_*	Mean rate of star formation, averaged over the lifetime of the Galaxy
f_p	Fraction of stars that have planets
n_e	Average number of planets in a planetary system suitable for life
f_l	Fraction of suitable planets on which life actually develops
f_i	Fraction of life-bearing planets on which intelligent life develops
f_c	Fraction of intelligence-bearing planets on which the capacity for interstellar communication develops
L	Average lifetime of a technological civilization

Fig. 1 *The Drake Equation relates seven factors that influence the possible number (N) of intelligent extra-terrestrials in our Galaxy, that may communicate with us. (Credit: David Darling)*

In reference to the Fermi Paradox, this essay will discuss components of the Drake Equation which will lead into a discussion of the handful of halting theories put forward over the last few decades. These are The Great Filter (Hanson 1998), the GRB Sterilization Theory (Annis 1999), the Lost Civilization Theory (Shermer (2002), the Cronus Theory (Bradshaw & Brook 2009), the Medea Theory (Ward 2015) and the Gaian Bottleneck (Chopra & Lineweaver 2016). I will provide a reasoned response to the need and value of halting theories – that they essentially halt the Drake Equation as effectively as they halt life.

2. THE DRAKE EQUATION

Dr Melvin Calvin won the 1961 Nobel Prize in chemistry for his discovery of the Calvin Cycle, a sequence of chemical pathways that turn the products of photosynthesis into sugars for the plant (Calvin 1949). In the laboratory, he subsequently arced a mixture of CO_2, H_2 and H_2O to simulate cosmic ray excitement in an atmosphere and discovered he'd created CH_2O, CH_2O_2 and $C_2H_4O_3$, all of which are potential precursors for the building blocks of life (Drake 1994). Drake soon discovered that Calvin had previously written "*We can assert with some degree of scientific confidence that cellular life as we know it on the surface of the Earth does exist in some millions of other sites in the universe*." This, along with the subsequent and more famous Urey and Miller experiments, got Drake thinking about what "…*we need to know about to discover life in space*?" (Drake 1994).

So Drake thought about how he and his colleagues would address this question at an upcoming meeting. He reasoned that we'd need to know how many stars with an Earth-like habitable zone *could* be created each year, as well as the proportion of them that *would* develop. He then realized that we'd need to know the likelihood of life arising on a planet at all, if it would evolve, if it became intelligent, if it survived to be spacefaring and to communicate across space. He went to the meeting with the formula mentioned above:

$$\mathbf{N = R_* \,.\, f_p \,.\, n_e \,.\, f_l \,.\, f_i \,.\, f_c \,.\, L}$$

Each of the terms in the original Drake Equation have been scrutinized in the literature, and several scientists have suggested adding extra terms. I will discuss each term.

N (the Drake Number)

N is the first term and needs defining. It has limitations that should be kept in mind. What we are assessing here, is the amount of '*advanced*' single, star-system populations *in the Milky Way*, who are, *today*, *capable* of using the *electromagnetic spectrum to communicate* across space. They are therefore in our "*past light cone*", a gedanken or thought experiment that allows us to visualise the causative past that leads to an event – in this case the event of a communication signal reaching us from far-off (and therefore in the past) space (Minkowsky 1908).

I have italicised some words in the previous paragraph because they each imply some interesting assumptions, not all of which are considered fully in the terms of the overall equation. The latter concept - that of a potential contactor being in our past light cone implies that, similarly to the fact that we have a finite observable visible universe (Lineweaver & Davis 2005), we can only expect an electromagnetic signal from a maximum of some 46 billion light years away.

Communication using gravitational waves, or the weak or the strong nuclear forces, is beyond current human technology, as are other technologies including time travel, worm holes etc, so the Fermi Paradox can be successfully debated on these 'what if?' grounds. It is a difficult process to think further about these exotic technologies and impossible energies needed to manipulate such technologies, and in any case they act on the large scale structure of the universe and don't effect the internal processes of a gravitationally bound system like our Galaxy (Gato-Rivera 2006).

As will become apparent, the Fermi Paradox as well as the Drake Equation are constrained by definition and perhaps science, to the Milky Way galaxy.

R_* (star formation rate)

This is the star formation rate (SFR) within our Galaxy. Estimates of this value are within our technology, and are derived by both theoretical and observational means, and range around 1 $M_\odot$ per year (see Robitaille & Whitney 2010, Licquia & Newman 2015, Marciel & Rocha-Pinto 2012). This is encouraging for a solution to the Drake Equation, because at least we have a reasonably tight constraint on this term. Fig. 2 is a graph lifted from Marciel & Rocha-Pinto (2012) and

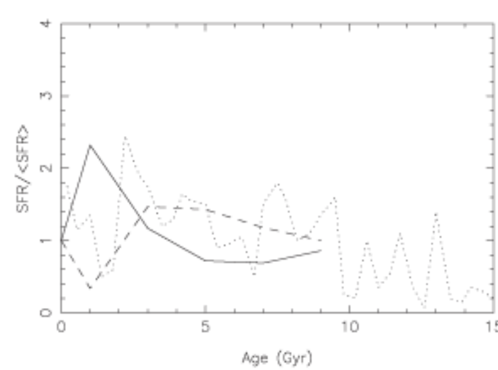

Fig. 2 *Various attempts at quantifying the Milky Way's overall star formation rate have agreed on a value roughly around 1 solar mass star per year. (Credit: Maciel & Rocha-Pinto)*

shows data points on a chart of SFR over the age of the Galaxy, both past and predicted, from various authors.

Keep in mind that this is a SFR of solar-mass average stars, so in terms of the Fermi Paradox, we are talking about ETI that evolves around a star that is like the Sun, with all the attendant assumptions of if, how and what could and would and did evolve other than on Earth. This has an obvious anthropic bias but is nonetheless a place to start.

Using stellar radioisotope dating, nucleocosmochronolgy attempts to derive an overall age of the Galaxy from examination of the apparent age of its components. This not insignificant task is muddied by the lack of precision in current galaxy evolution theory, but the spiral arms of the Galaxy, where SFR is high, are at least around 10 billion years old (Robotham 2012). Also given the life expectancy of the Sun of about 10 billion years (NASAweb1), this surely means that at any one time during the lifetime of the Galaxy, there are 10 billion solar-type stars.

If these stars were spread evenly around the volume of the Galaxy (and of course they're not!), how far apart would they be? The volume of the Galaxy is around 2 x 10^{13} cubic light years (Plaitweb), so dividing by 10^{9} stars, we get a volume of 2 x 10^{4} cubic light years per star. So the nearest neighbour of the average star will be about $(2 \times 10^{4})^{1/3}$ light years away. A mere 27 light years – which I will round up to 30. A radio signal would take around 30 years to reach between these stars, and humans have been producing intelligible (?) radio signals for about 100 years (Teslaweb), and an ETI targeted signal, the Arecibo Massage, was sent by Drake in 1974 (SETIweb2).

Perhaps therefore, R_* = 1 and has no effect on the value of **N**

f_p (fraction of R_* that have planets)

As mentioned above, Shapley floated the possibility of ETIs evolving on Brown Dwarfs by using Infra-Red radiation as an energy source, but for the furtherment of this discussion, I will take Drake's implied assumption that they inhabit a planet around the aforementioned Sun-like stars. So, how many of these one-per-year, solar-mass stars, have planets?

This part of the argument employs the hopeful and recent breakthrough in detections of extra-solar planets, exoplanets, specifically by the Kepler Space Telescope (Keplerweb). At the time of writing, the repository of exoplanets, Exoplanet.eu, has 3,608 in the catalogue (ExoPweb). These are not all within the Milky Way, but the outcome of this decennia-old science has alerted us to the fact that there are very many exoplanets. Other studies, like NASA's Probing Lensing Anomalies NETwork (PLANET) use gravitational microlensing (see Zakharov 2016) as a good detection method and five years ago suggested there are 10 billion *terrestrial* planets in the Galaxy, and at least 1,500 planets within 50 light years of us (NASAweb2).

Guestimates of the percentage of stars that have planets at all, vary up to 100%, and are becoming more confident by the month. The recent discovery of seven Earth-sized planets around a single star just 40 light years away (TRAPPISTweb) has strengthened the argument that if there are several billion stars in the Galaxy, then it is likely that there are the same number of planets. This means the fraction of likely stars with a planet is unity.

Perhaps therefore, $\mathbf{f_p} = 1$ and has no effect on the value of **N**

So far there are two terms that can be quantified being unimportant to the outcome of Drake's Equation!

$\mathbf{n_e}$ (number of planets suitable for life) and

$\mathbf{f_l}$ (number of habitable planets where life *does* exist)

Here is the first low sigma problem with the Drake Equation that taps straight into Fermi's Paradox. The problem is the vague phrase "suitable for life". And because of the sequential, mutually inclusive, thought process employed by Drake when he put this equation together, the subsequent terms are more and more reliant on this term, and more and more uncertain as a result.

The terms are not mathematically independent. Drake's Equation is a polynomial function of the dependent variable N, with two somewhat independent variables (**$\mathbf{R_*}$** and **$\mathbf{f_p}$**) and four dependent/interdependent variables. As shown, we may be able to input some quantities for the quasi-independent variables **$\mathbf{R_*}$** and **$\mathbf{f_p}$** but are then confronted with a string of interdependent variables, all based on this first one **$\mathbf{n_e}$** . This is a formula, but not a formula for success and will be discussed below.

But Drake intended this to be a radiant point for discussion, so I push on to ask: what is life? And what makes a planet suitable for life to initiate and, presumably evolve? Since there is just one example of our self-defined (that's an anthropic bias issue right there!) life, the definition must logically resort to factors that are absolutely fundamental. A living entity is essentially a heat engine (after Carnot 1824) locally disobeying the second law of thermodynamics. It requires a renewable energy source from which to derive its potential to do work, that is, live. Without implying intent or reason, this entity exists by (actively or passively according to its design) harvesting resources from its environment, processing said resources, managing any unuseful by-products, and employing some kind of process to ensure it is more than just a single individual that will perish, but rather replicate itself before it senesces out of existence.

If Drake's Equation is asking how many of Fermi's *intelligent* lifeforms are out there, then the assumption is that the planets that harbour *any* life will include those with the most *fundamental*, so the search is most efficient if very simple organisms are sought. The first requirement - an energy source can be worked up from the four (known) basic forces in the universe known to humans – weak and strong nuclear, gravity and electromagnetic. (although Riordan 2017 gives a good summary of a potential fifth force) Unless extreme science fiction is employed, organisms that use either of the first three are… not possible. Electromagnetism holds the living, baryonic world together, mostly through chemistry, so life as we know it exists in environments with liquid water in sufficient quantities to facilitate chemical reactions as a metabolism.

Baryonic, electromagnetic elements are obviously widespread in the Galaxy, in stars and on planets, moons, asteroids, comets etc, but the presence of liquid H_2O is constrained to habitable zones around stars (Strughold 1953 and many since). So any subsequent discussion about intelligence, communicability and technological survival – the Drake terms $\mathbf{f_i}$, $\mathbf{f_c}$ & **L**, seems moot unless and until life in a habitable zone evolves. If Fermi proceeded from the assumption that a technologically communicative lifeform would surely have had time to appear, evolve and expand enough to contact Earth, then this is the part of the assumption that is weakest. If only for the fact that there is no reference lifeform.

3. DRAKE ADDENDA

Before I discuss halting theories, I will cite a few of the works done by others who added caveats and terms to the Drake Equation. This is to give the reader a fuller sense of the subject before I break the Drake in half at the middle.

Bracewell (1976) suggested an additional term that incorporates the networking capability of intelligent, communicative lifeforms especially as they face the uncertainty of their own fate. As with any discussion about terms after $\mathbf{f_l}$, this is on shaky ground as explained above.

Walters et al. (1980) would like to see a term that quantifies the ability to create colonial star systems because communication between these and home planets would be by electromagnetic means, and so humans should continue the Search for Extraterrestrial Intelligence (SETI) with radio astronomy. This sounds like a continuation of Fermi's assumption that ETIs are a fait accompli.

Papagiannis (1982) adds a term allowing for resource-mining civilizations who's home planet perished not before they established colonies in the asteroid belt. The suggestion is that they are there now! The suggestion that there may be probes belonging to now-perished civilizations has some merit. But are these Bracewell-von Neumann (Webb 2015) probes within the definition of life? Does it matter?

Delsemme (1995) believes that because planets are formed from accretion of bodies with no water, gases or carbon, then these ingredients must be brought to the protoplanet with the aid of some gas giants' gravitational influences on comets. Therefore a Drake term should include the terrestrial/gas giant ratio of a system. This is probably best incorporated in the $\mathbf{n_e}$ term, but as mentioned above, still subsequently needs a definition of life. We have a long way to go before we can characterise this ratio in Galactic solar systems.

Schenkel (1999) debated that the longevity of ETIs was indefinite and that humans would not destroy themselves but evolve towards the same peaceful, unlimited future. Boosting the size of Drake's L factor was recommended. A paper typical, perhaps of the time it was written, and of the socio-political input into the Drake Equation. For the purposes of providing a justifiable view in this essay, this is not helpful.

Chela-Flores (2000) focussed down on the same spot I have in this essay. The key point from which intelligent life may evolve, is the evolution of eukaryotic cells and multicellularism, which appear to be likely to be found in solar system environments like Europan oceans. Again, a boost for the $\mathbf{f_i}$ term. As I will argue, though, the halting theories have much to say about the evolutionary success of such populations.

Balázs (2000) puts a Keplerian twist into the discussion by suggesting that Galactic civilizations are protected from inevitable impact destruction if they're located in a calmer region incorporating the co-rotating disk of the Galaxy and our solar system. An interesting concept that might be incorporated into the $\mathbf{f_l}$ term – which still suffers the emergence of life problem.

Musso (2001) believes that marine civilizations cannot evolve to intelligence, thus restricting ETIs to dry, tectonic planets. Some strong assumptions are made in this paper, and would need some seriously strong proofs to go with them. For example, that life is harder on land than in the water. In any case, a consideration.

Finally, Rubin (2001) acknowledges L is a vague, self-contradicting and hard term to define and is only likely to represent human anxiety about their future. I think that's correct and a great subject around a dinner table.

These selected authors display a range of views over a few decades. I still think the most fruitful point to focus on the Drake Equation is where it breaks down – as soon as the biological terms appear.

4. HALTING THEORIES

As mentioned in the introduction, there are a handful of theories that address this issue of entering the biological phase of the Drake Equation. Typically, they concentrate on the ability of proto-life to evolve past global physical or environmental catastrophies, but I will also include some that halt progress later in the equation.

In anticipation of references to Gaia Theory, I will briefly draw the reader's attention to James Lovelock's 1965 theory which posits that terrestrial organic and inorganic systems work in a positive feedback system over geological times and global environments, to positively *ensure* the survival of life on earth (Lovelock 1965).

Also interesting is Richard Dawkins' 1982 remark about Lovelock's Gaia Theory :

"*For the analogy [of the Earth as an organism] to apply strictly, there would have to have been a set of rival Gaias, presumably on different planets. Biospheres which did not develop efficient homeostatic regulation of their planetary atmospheres tended to go extinct. The Universe would have to be full of dead planets whose homeostatic regulation systems had failed, with, dotted around, a handful of successful, well-regulated planets of which the Earth is one*." (cited in Chopra & Lineweaver 2016). As an evolutionary biologist, I think Dawkins makes a very good point – why wouldn't we consider the entire universe as one single ecosystem? But this leaves us wanting for a response to Fermi's Paradox.

The Great Filter (Hanson 1998)

A primary source for the argument for some kind of cosmic hiatus that stops the process from inanimate materials to a communicating ETI, is Hanson's 1996 (updated 1998) online precis from an economists view. In it he identifies at least nine development steps [*my comments to the right*]:

1. A habitable solar system, [*similar to Drake's* $\boldsymbol{R_*}$. $\boldsymbol{f_p}$. $\boldsymbol{n_e}$. $\boldsymbol{f_l}$]

2. Biomolecules that can replicate, | *Are these really*
3. Prokaryotic cells, | *critical steps*
4. Eukaryotic cells, | *or an inevitable*
5. Sexual reproduction, | *phase of biological*
6. Multicellularism, | *transitions?*

7. Evolution of an intelligent species, [*similar to Drake's* $\boldsymbol{f_i}$]
8. Contemporary human society, and [*similar to Drake's* $\boldsymbol{f_c}$]
9. Galactic expansion. [*qv Drake's* **L** *term & speculative Kardashev Scale*]

Hanson assumes the "…*fact that our universe is basically dead*…" and therefore concludes that one of these steps is a critical failure point – a Great Filter. If, he goes on to say, there is a Great Filter, then our problem is that humans don't know *when* it is, other than that we are already at step eight and this does not not bode well for us because we will clearly not make it if the Great Filter is in our future. I think this is very sloppy and narrow minded thinking.

First, notice that Hanson is looking back through evolutionary phases and attributing critical significance to certain of them *as if he knows* they are critical. I know of no reason to assume such. Also notice that there is but one identified stage ahead of us. This means nothing when Hanson applies his poor logic to say that because scientists have shown plausible explanations for steps 1-8, then life must exist elsewhere in the Galaxy. That essentially means there is one phase behind us and one phase ahead of us – a self-cancelling, non-statement. Hanson's subsequent arguments about the biological details of each step, and how they must be critical, are self-protecting non-sequiters. He is clearly suffering anthropic bias, and in my view makes a very week argument for any sort of filter existing.

What Hanson does do, is provide the kernel of an idea from which others have progressed: the idea that a halting phase/event exists at some time during the evolution of life.

A GRB Sterilization Theory (Annis 1999)

Annis contends that the 10^8-year period that Fermi and others (qv Tipler 1981) calculate for the period of time it should take a civilization to expand over the Galaxy, is very similar to a possible quiescent phase of GRB activity. GRBs are Gamma Ray Bursts. Serendipitously discovered by a spy satellite in the late 1960, GRBs can release as much energy in a few seconds, as the Sun will emit during its whole lifetime (SAOweb1, Webb 2015), and this radiation may have two relevant consequences. First, a GRB detonating in our Galaxy may effectively extinguish all living activity in the Galaxy, so we might not expect a civilization like ours to evolve much more frequently than humans have.

However, there is a second suggestion (McBreen & Hanlon 1999) that a GRB 4.5 billion years ago near the proto-Solar System fused some of the accretion disk material and created chondrules as they cooled. This implies that our rocky planet derived their metals from accretion of chondrules, hence giving us a rare set of raw materials to use and a terrestrial planet to stand on. An intriguing theory, and an ADSABS search revealed all 8 hits for the words 'GRB and chondrule', to be work including McBreen as author. Chondrules are known to be formed under flash-heat circumstances early in the formation process of the Solar System (SAOweb2), so this is high a support for Fermi's observation.

The Lost Civilization Theory (Shermer 2002)

I include this here as an example of an informal theory often espoused. Dr Michael Shermer is, amongst many other things, founder and Publisher Editor-in-Chief of the Skeptics Society as well as scientific advisor to the American Council on Science and Health (SSweb). Also a lecturer in skepticism, Shermer notes the lamentations of Seth Shostak (SETI) and Robert Zubrin (Mars Society) over the extreme vagueness of the last Drake term, L. The calculation of N is exquisitely sensitive to the input value of L.

Where other luminaries like Sagan arrive at a figure for N in the thousands or millions, Shermer makes his point by averaging the lifespan of scores of human civilizations, arriving at a value of N around 2 or 3 depending on how you classify civilizations. He claims that so few intelligent, communicative species in our Galaxy, explains why no-one has said hello (Shermer 2002).

I think Shermer is either being incredibly naïve, or his tongue is firmly in his cheek. Using terrestrial civilizations' lifespans as a yardstick for the lifespan of an as-yet-unidentified ETI is just – not logical. There are so many factors that can differently influence the longevity of a community of beings whose biology we haven't yet even discovered: energy source and derivation, planetary resources and environmental support capability, evolutionary development, social and technological evolution, chemistry, physiology and metabolism, innate rates of learning and motivation, extinction events. Etc. I cannot see how Shermer is serious.

Bostrom's Bottleneck (Bostrom 2008)

Prof. Niklas Boström is Director of the Future of Humanity Institute and Director of the Strategic Artificial Intelligence Research Centre at University of Oxford (NBweb). He subscribes to Hanson's Great Filter idea and believes it would be bad news for humanity's future if an ETI was discovered. He believes, unlike most, that the biggest threat is not at the emergence of life, but the contemporary fatalistic view that we are in a self-destructive bottleneck. This would mean that the future of humanity is doomed to face an extinction event in the future – that the Great Filter is ahead of us.

Bostrom seems to be neutral on Fermi's Paradox, but thinks it's a useful tool for assessing "*…existential risk…*" (Chopra & Lineweaver 2016). He takes Fermi's Paradox, correctly I believe, to be a gedanken to seed ideas about human evolution.

As an aside, Bostrom later wrote a "Letter from Utopia" in which he assumes the position of an advanced space-faring species who are offering their wisdom. In the letter, the Utopians advise humans to extend their biological lives in anticipation of evolving into a non-corporeal form, advance their cognitive abilities greatly, and manage their hedonistic tendencies better (Bostrom 2008).

The Medea Theory (Ward 2009)

Prof. Peter Ward is a palaeontologist, science writer, Geological Society of America Fellow and adviser to the Microbes Mind Forum (UWweb). The magazine New Scientist's lead article of 18 June 2009 was Wards new theory about the repeated extinction events that have occurred on Earth over geological time. This is in part a response to the Gaia (or Earth Feedback) Theory (Lovelock 1965) which posits that terrestrial organic and inorganic systems work in a positive feedback loop over longer times, to *ensure* the survival of life.

Ward considers what he identifies as the many extinction events since the formation of Earth, a looming self-annihilation, and future planet-wide sterilizations:

- the methane crisis 3.7 Gya,
- the great oxidation event 2.5 Gya,
- several ice ages,
- eight mass extinctions from the ordovician to the paleocene/eocene,
- an identifiable human extinction event of current times (holocene or anthropocene),
- planetary loss of oxygen and plant life destroyed in 0.5 Gy in the future, and
- a sterile planet in 1 Gy time.

Ward relates each of these halting events to the tendency for the global microbial ecosystem to periodically overwhelm all other life forms in an attempt to return the Earth to its rightful inhabitants: the microbes. It is meant as a direct argument against Lovelock's positive and optimistic Earth, by proposing a negative and pessimistic reality.

The Medea Theory thus provides a potentially very high sigma solution to Fermi's Paradox – life on terrestrial planets is likely to succumb to any number of halting events in just a few billion years of trying to evolve into an intelligent, space-faring species. Unfortunately, Ward doesn't consider the different starting dates for the origins of life. Presumably, the counter argument would be that given the large range of planetary system ages, there would be plenty of time for some to evolve, and one would expect there to be a large number of ETIs who are sufficiently advanced *now*, to be in contact with us.

The Cronus Theory (Bradshaw & Brook 2009)

Prof. Corey Bradshaw was the Sir Hubert Wilkins Chair of Climate Change, and is now the Matthew Flinders Fellow in Global Ecology. He is an award winning, and highly cited author (CBweb). Prof. Barry Brook now holds the Sir Hubert Wilkins Chair of Climate Change and is Director of Climate Science at the University of Adelaide and Australian Research Council Future Fellow. He was the 2010 Community Science Educator of the Year (BBweb).

Bradshaw and Brook (2009) respond to the Gaia and Medea extremes by suggesting that terrestrial life is a "…*scale-invariant stability-entropy spectrum of speciation*…" – essentially a fluctuating range of attempts to exist on a long-scale thermodynamic potential scale. The authors consider that instead of the global ecosystem behaving like a single entity, each species behaves like an individual in a population and Cronus Theory is a metaphor for how to study the epidemiology of halting events for the entirety of life on Earth.

This theory doesn't directly inform about the Fermi Paradox, but it moderates the 'boom or bust' versions created by Lovelock and Ward. It implies that with applied knowledge and resources, it might be possible for an intelligent species to overcome a halting event like the current Anthropocene Extinction – which is defined by a large increase of extinctions caused by humans, over and above the background extinction rate (Ceballos et al, 2015). If Bradshaw and Brook are right, then Fermi may have a point. There must surely be enough time, evolutionary variation and resources 'out there' for an intelligent species to evolve past a halting event and go on to explore the Galaxy.

The Gaian Bottleneck (Chopra & Lineweaver 2016)

Dr Aditya Chopra is a planetary scientist and post-doctoral student at the University of Washington (ACweb). Dr Charley Lineweaver is Senior Fellow, Planetary Science Institute and often speaks at public seminars in his fields of interest: astrobiology, cosmology and planetology (CLweb).

Their 2016 article in the Journal Astrobiology, exhaustively synthesises the whole question of why we don't see extraterrestrial life around us. The emergence-of-life bottleneck is the commonest explanation, they say, because it is chemicophysically complex and risky. Their proposed Gaian Bottleneck theory describes how uncommon it must be for a species to evolve quickly enough to outrun its own negative modification of its environment, and that "…*extinction is the cosmic default*…" (Chopra & Lineweaver 2016). Importantly I think, their theory is confined to life that requires water and a rocky terrestrial planet.

5. CONCLUSIONS

The aim of this essay was to review the arguments and assumptions that produced Fermi's Paradox in 1950, and to arrive at a resolution for the paradox. My response has been to provide a general historical overview of the paradox itself, a discussion of the subsequent Drake Equation, and some focus on validity of various halting theories that have been proposed.

As I mentioned in the first paragraph, nothing peer-reviewed was published for 25 years (see Hart 1975) after Fermi asked, not "Why is there no ET life", nor "Isn't it strange we haven't seen ETI yet?", but more likely querying the physics of being able to travel between the stars (Gray 2015). As Gray points out, Hart was the first to suggest that there is a paradox between the likelihood of interstellar travel being possible, and the fact that we haven't been visited yet. Of course, this is a cheap shot, and still begs the question that was asked under Fermi's name anyway.

In this essay, I have shown that the Drake Equation has two parts:
In the first part, terms for stellar formation rate and for the fraction of stars with planets, are both likely to be around unity, so their effect on Drake's number of Galactic ETIs is negligible anyway. The subsequent terms are very strongly inter-dependent, vaguely quantifiable, and the final term for how long an ETI civilization can survive is notoriously and universally, regarded as being a guess.

Second, the Drake Equation suffers critical failure as soon as the 'biological' terms are met. None of them are remotely quantifiable, the equation is mathematically questionable, and importantly, we *cannot* know their value. Yet. We don't even have a reference species based on exotic chemistry, or doesn't need liquid water, or lives on vacuum energy, or floats through the atmosphere of Sagan's Jupiter.

I see some high sigma possibilities in Bracewell-von Neumann probes existing, although not necessarily in our Galactic neighbourhood. I also see high sigma chances of a Dawkins-Ward type of universal ecology that results in extinct civilizations scattered around the Galaxy (Annis' GRB extinction theory is as controversial as GRB evolution theory itself!), though again, not necessarily near us.

Halting theories are interesting. Is it possible to identify the cosmic potholes for a solitary, ill-defined, consciousness when we are inside it? I think not. We can imagine and theorise, but from zero statistical evidence. We must surely assume, and hope that we are a cosmically young species. To do otherwise would be suicidal.

In closing, Fermi's Paradox is entertainment. Humans have no real reason to think it's a paradox or not. It is perfectly good, right and proper to not know the answer, and to hold judgement while we keep our minds open and explore for 'our kind of life' while being vigilant for exotic life.

There is no Fermi Paradox.

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