How Rare is Rare?
Evaluating the Rare Earth Hypothesis

"Life is a foreign language; all men mispronounce it."
—Christopher Morley (1890 - 1957)

Submitted by:
Dennis Ward
HET-616
1 November 2002

Project Supervisor:
Sara Ellison

Introduction

The Copernican Revolution showed that all the planets were worlds orbiting the Sun, itself simply one of myriad stars. From here it was a short leap to wonder if other worlds, both around the Sun and other stars, might also harbor life. Respected astronomers such as Bode, Ferguson, and Herschel believed that life might be found as near as the Moon (Ferris, 2002). Even William Pickering believed that he had observed canals, vegetation, and insect swarms on the surface of the Moon. He boasted to his brother in a 1912 letter that he had "seen everything practically except the selenites themselves running round with spades to turn off the water into other canals" (Crowe, 1986).

Perhaps the peak of interest in extraterrestrial life came during the first three decades of the 20th century. In 1877, Schiaparelli reported seeing *canali* (denoting straight, linear features) on the surface of Mars. Percival Lowell devoted the last 23 years of his life to observing Mars and describing the signs of life that he thought he had observed on its surface (Dick, 1998). However, observations made in the 1920s showed that Mars was much colder with a thinner atmosphere than Earth's, and as a result discussion about life on Mars dwindled. The debate about extraterrestrial life remained dormant until the dawn of the space age (and the emergence of science fiction) in the 1950s.

The Drake Equation

In 1960 Frank Drake began his career at the National Radio Astronomy Observatory (NRAO). He used the 85-foot (25.9 m) radio telescope to search for artificial signals from two nearby sun-like stars, Tau Ceti and Epsilon Eridani, for two months. Although he found nothing in this seminal search, which he named Project Ozma, it was the beginning of a new research field—the search for extraterrestrial intelligence (SETI) (Shostak, 1998).

In 1961, Drake held a meeting with selected scientists, including Carl Sagan, to discuss the practicalities and pitfalls involved in SETI research. It was during this meeting that Drake first presented what has become known as the Drake Equation, where N (number of observable civilizations) is defined by:

$$N = N^* \bullet f_p \bullet n_e \bullet f_l \bullet f_i \bullet f_c \bullet f_L \qquad (1)$$

N^* is the number of stars in our galaxy, f_p is the fraction of those stars that have planets, n_e is the average number of potentially life-bearing planets in a typical solar system, f_l is the fraction of those planets on which life actually forms, f_i is the fraction of life-bearing planets where intelligence evolves, f_c is the fraction of intelligent species that develop interstellar radio communication, and f_L is the average lifetime of a communicating civilization in years (Sagan, 1980).[1]

---

[1] As is obvious, this equation is a crude approximation since it produces real numbers rather than positive integers. A more contemporary approach would be to define the distribution of stars and have that distribution be governed by the kinds of parameters that Drake introduced into his now famous equation.

During the 1980s, Carl Sagan became probably the most well-known science popularizer in the world. He was also at the forefront of planetary scientists looking for signs of life on other solar system bodies. Together, Sagan and Drake accelerated SETI research by showing that there might be millions of extraterrestrial civilizations in the universe.

For almost 40 years, the Drake Equation deftly broke up the issue of SETI into smaller questions that researchers have been able to study, creating better estimates of N. In 1974, Sagan estimated that our galaxy alone might contains upward of a million civilizations (Ward & Brownlee, 2000). This figure has been widely accepted and has helped gain support for SETI research. However, no one seemed willing to question the basis of the Drake Equation itself.

The Rare Earth Hypothesis

In 2000, a pair of scientists from the University of Washington published *Rare Earth: Why Complex Life Is Uncommon in the Universe*. In it, they question many of the underlying assumptions of the Drake Equation by positing what they call “the Rare Earth Hypothesis.”

The Rare Earth Hypothesis (REH) is the “unproven supposition that although microscopic, sludge-like organisms might be relatively common the planetary systems, the evolution and long-term survival of larger, more complex, and even intelligent organisms are very rare (Ward & Brownlee, 2000).”

The Rare Earth Equation

Ward and Brownlee presented their hypothesis in equation form, much like Drake did 39 years earlier:

$$N = N^* \bullet f_p \bullet f_{pm} \bullet n_e \bullet n_g \bullet f_i \bullet f_c \bullet f_l \bullet f_m \bullet f_j \bullet f_{me} \qquad (2)$$

N^* is the number of stars in the Milky Way galaxy, f_p is the fraction of stars with planets f_{pm} is the fraction of planets that are metal-rich, n_e is the planets in a star's habitable zone n_g is the stars in a galactic habitable zone, f_i is the fraction of habitable planets where life does arise, f_c is the fraction of planets with life where complex metazoans arise, f_l is the percentage of a lifetime of a planet that is marked by the presence of complex metazoans, f_m is the percentage of planets with a large moon, f_j is the percentage of solar systems with Jupiter-sized planets, and f_{me} is the fraction of planets with a critically low number of mass extinction events. Using their Rare Earth Equation, Ward and Brownlee make the argument “that Earth indeed may be extraordinarily rare (Ward & Brownlee, 2000).”

One must remember that there is a fundamental difference between the two equations. The Drake Equation is designed to determine the probability of *finding* extraterrestrial intelligence. The Rare Earth Equation, on the other hand, is designed to predict the *existence* of complex life and has nothing to do with finding it.

Some of the factors presented by Ward and Brownlee (2000) are similar to those in the Drake Equation, some are slightly revised, and others totally new. In the remaining sections of this paper, I briefly discuss the factors that are common to both equations and then discuss the “Rare Earth” factors in more detail. Finally, I analyze results from both formulations.

Common Factors

There are five factors common to both the Drake and Rare Earth Equations.[2]

Number of Stars in Our Galaxy (N^*)

Current estimates of the number of stars in our galaxy place N^* at somewhere between 100 and 200 billion stars. In later versions of the Drake Equation, N^* was replaced by R^* which represents the rate of star formation in our galaxy. The Rare Earth Equation uses N^*, and I use the older version of the Drake Equation to simplify the comparison and presentation of the two equations.

Sun-like Stars (f_s) / Stars in Galactic Habitable Zone (n_g)[3]

Drake included the term f_s to represent the fraction of “sun-like” stars that might exist in our galaxy. This is a rather broad-reaching term, open to quite a bit of interpretation. For example, in what way are they similar to the Sun? Do they share similar spectral classes? How about their location within our galaxy, or their age and metallicity? Ward & Brownlee approached this term in a slightly different manner. Instead of saying the star must be sun-like, they approach this term by asking what fraction of stars are found within our galaxy’s “habitable zone,” which they refer to as n_g. This habitable zone is a region of the galaxy defined as “that region in the Milky Way where an Earth-like planet can retain liquid water on its surface and provide a long-term habitat for animal-like aerobic life (Gonzalez, Brownlee, & Ward, 2001).” Since the Sun is located within this region, all other “Sun-like” stars would be as well.

Stars with Planets (f_p)

For the first 30 years of research into the Drake Equation, the fraction of stars with planets was totally unknown. Many astronomers believed that planets should be common—formed from the remnants of each star’s birth. Sagan once estimated that approximately one-third of star systems might have planets (Sagan, 1980). Thanks to the 1991 discovery of extrasolar planets orbiting pulsar 1257+12, this factor was increased by a factor of two, since the number of known planetary systems suddenly jumped from 1 (the Solar System) to 2 (Wolszczan, 1991). During the following 11 years, over 100 planets have been found in more than 85 planetary systems (Greene, 2002a).

Based on the results of a 15-year survey headed by Paul Butler and Geoff Marcy, approximately 12 percent of the Sun-like stars in our galaxy have planets that can be detected orbiting their stars within about 5 AU (Greene, 2002b). These discoveries have been invaluable—by proving that f_p is non-zero (besides our solar system), they have eliminated one major obstacle to SETI. We now know for certain that our solar system is not alone in the universe.

---

[2] Although there are subtle differences between the use and interpretation of these factors in each equation, they can be considered functionally equal in application.

[3] Throughout this discussion, pairs of factors separated by a “/” present the Drake Equation factor followed by the corresponding Rare Earth factor.

Planets in a Star's Habitable Zone (n_e)

A recent study has modeled a few extrasolar planetary systems that are known to contain giant planets. The investigators added terrestrial planets to the numeric models of the planetary systems and ran n-body simulations to determine if these theoretical planets would have stable orbits within each star's habitable zone. In at least two cases, the models show that a terrestrial planet in the appropriate orbit would stay within the star's habitable zone for biologically-significant time periods (Jones, Sleep, & Chambers, 2001). While this does not prove that planets actually exist in these orbits, it does show that terrestrial planets orbiting within the appropriate zones could be in long-term stable orbits.

Planets with Life (f_l & f_i)

Both the Drake and Rare Earth Equations contain factors that denote the fraction of planets that harbor life. It is interesting to note however, that neither equation requires a particular definition of life. They do not stipulate that life has to be Earth-like, for example.

Rare Earth Factors

In addition to the common factors that have already been discussed, there are two factors that are roughly comparable between the two equations and four that are truly unique to the Rare Earth Equation. In this section I discuss the two comparable factors first and follow up with the unique Rare Earth factors.

Planets with Intelligent Beings / Complex Metazoans (f_c)

This is perhaps the hardest factor to define, let alone quantify. In the Drake Equation, f_c is defined as the fraction of civilizations that have the ability and desire to communicate over interstellar distances (Shostak, 1998). This definition makes some wide-reaching assumptions, namely that all intelligent life forms will develop both radio communications and radio telescopes. This definition has drawn criticism during the past few decades, as it is somewhat myopic for a radio astronomer to assign intelligence to only those civilizations that become radio astronomers.

On the other hand, the Rare Earth Equation is not dependent on intelligent life. Instead, it defines f_c as the fraction of planets that develop life in the form of complex metazoans. A complex metazoan is defined as a life form that has developed past the single cell stage. In other words, a complex metazoan is a multi-celled organism. The past 500 million years of Earth's history has included complex metazoans (Ward & Brownlee, 2000).

At this point, it becomes clear that although the Drake and Rare Earth equations are often viewed at two different ways in which to derive the same value, this is not the case. The Drake Equation serves to estimate the number of observable civilizations in our galaxy (and through extension, the entire universe). The Rare Earth Equation instead calculates the probable number of planets that harbor complex life forms, whether they are intelligent or not. Obviously, this is a crucial distinction

Fraction of Planets Lifetime with Communicative Civilization / Complex Metazoans (f_L/f_l)

The last remaining factor from the Drake Equation is f_L, the portion of a planet's lifetime during which a civilization capable of interstellar communications exists. This factor seems to have been born out of the Cold War between the US and the USSR during the 1960s. Carl Sagan was particularly concerned with this, believing that any civilization that arose after billions of years of tortuous evolution only to destroy themselves in the blink of an eye was "guilty of unforgivable neglect (Sagan, 1980)." One might wonder what value Sagan would apply to this factor in today's post-Cold War world. However, the underlying logic is still valid—the longer a communicating civilization survives, the more likely it is to be detected. Of course, the ultimate limit to this factor is the lifetime of the planet's host star. In our case, the Sun will begin to expand rapidly, becoming a red giant and making the Earth uninhabited, in approximately 4 billion years.

The Rare Earth Equation was developed in the final years of the 20th century, and doesn't reflect the social factors that seem to have concerned Drake and Sagan. This doesn't mean that this factor is unimportant to Ward and Brownlee. Quite the opposite is true—their book lists a number of factors that tend limit both f_c and f_l.

The remaining factors in the Rare Earth Equation serve to greatly reduce the number of Earth-like planets. If you took all the factors discussed to this point and assigned the same values to both the Drake and Rare Earth Equations, you would of course derive the same number (remembering that the two equations are actually calculating different things). By setting the following four factors to values less than 1, the Rare Earth equation drives down the final result to an even lower number.

Planets with a Large Moon (f_m)

One of the more interesting Rare Earth factors is the fraction of planets that have a large moon. When compared the moons orbiting other planets in our solar system, the Moon is unique. The Moon is only one of three moons that are known to orbit the terrestrial planets, the other two being Phobos and Diemos, which orbit Mars. These Martian moons are but 10 km in diameter, while the Moon is approximately 3,500 km in diameter. The Moon is nearly one-third the size of the Earth, and is sometimes referred to as the Earth's twin.

According to the REH, the Moon plays three roles in the development and survival of life here on Earth (Ward & Brownlee, 2000). It:

- causes lunar tides,
- stabilizes the tilt of the Earth's spin axis, and
- slows the Earth's rotation rate.

The most important of these three roles is its stabilizing effect on the Earth's tilt, or obliquity. Obliquity is of course the source of the seasonal changes in climate. The Earth's obliquity has remained constant at approximately 23° for hundreds of millions of years. Absent the Moon, this axial tilt could vary by as much as 90° (Ward & Brownlee, 2000), which would cause severe disruptions to the progression of the seasons.

The lunar tides, caused by the gravitational interaction between the Earth and the Moon, may have also played a pivotal role in the evolution of life on Earth, according to Ward and Brownlee. Current theories of the Moon's origin state that the moon was probably formed by the impact of a Mars-sized object with the young Earth. Such a creation scenario would have resulted in the Moon orbiting at a distance of perhaps 15,000 miles, as opposed to the 250,000-mile orbit it experiences today. At this distance, it might have caused tides with heights measured in tens of meters, rather than the much smaller (<3m) tides seen today in most locations. Such a close moon might have strongly heated the Earth's surface as well (Ward & Brownlee, 2000).

As the Moon slowly increased its orbital radius from 15,000 to 250,000 miles, an offset between Earth's lunar tidal bulge axes from the actual Earth-Moon alignment produced a torque that caused the Earth's spin rate to slowly decrease as the Moon retreated. Fossil records show that Earth experienced days much shorter day than the current 24-hour one. This too would have had a significant impact on the evolution of life on Earth.

It is therefore obvious why Ward and Brownlee added the f_m factor to the Rare Earth Equation. It seems unlikely that complex organisms could have evolved in an environment that experienced extreme seasonal and climate variations while at the same time experiencing a much shorter day.

Solar Systems with a Jupiter-sized Planet (f_j)

If the Moon was a major factor in the evolution of life on Earth, could other planets have played a roll as well?

During the past decade, astronomers have studied what affect that Jupiter might have played on the history of the Earth. Specifically, they have studied what effect the lack of a Jupiter-sized body might have had on the primordial Solar System. George Wetherill has estimated that the flux of cometary bodies in the region of the terrestrial planets would have been 1000 times the observed rate (Wetherill, 1994). Given our current understanding of impact hazards and their effect on the terrestrial biosphere, is it hardly surprising that the Rare Earth Equation includes the f_j factor.

Just as the estimates for f_p have progressed from pure guesswork to more accurate estimates due to the discovery of extrasolar planets, so have the f_j estimates improved in the past few years. There have been a number of so-called "hot Jupiters" discovered orbiting quite close to their host stars (Greene, 2002a). It is doubtful that these planets provide protection to any hypothetical terrestrial planets in the stars' habitable zones, as their orbits are inside the habitable zones. However, thanks to a discovery made in September of 2002, it appears that f_j can finally be assigned a non-zero value. A newly discovered planet with a mass of about 1.2 Jupiters has been found to orbit the star Tau 1 Gruis. It is located about the same distance from its star as our asteroid belt is from our Sun (2.5 AU) and has a roughly circular orbit (Greene, 2002b).

Planets with Mass Extinction Events Below a Critically Low Number (f_{me})

Perhaps the most original factor that contributes to the Rare Earth Hypothesis is the idea that a planet's history, as well as its location and environment, plays a major part in determining if life can develop to a complex level. As mentioned in the previous section, if Jupiter had not formed in the early Solar System, the flux of comets could have been as much as 1000 times what it has been through history. Every additional cometary fragment that enters the region occupied by Earth increases the probability that one of them will eventually impact the Earth. Figure 1 illustrates the observed relationship between meteor size and impact frequency, as well as the destructive potential of each class of impactor.

A 100 m meteor strikes the Earth approximately every 1,000 years. An impact of this magnitude is enough to devastate a region the size of a continent. Every million years the Earth is struck by a 1 km meteor, releasing enough energy to wipe out a global civilization and destroy all agriculture on the planet.

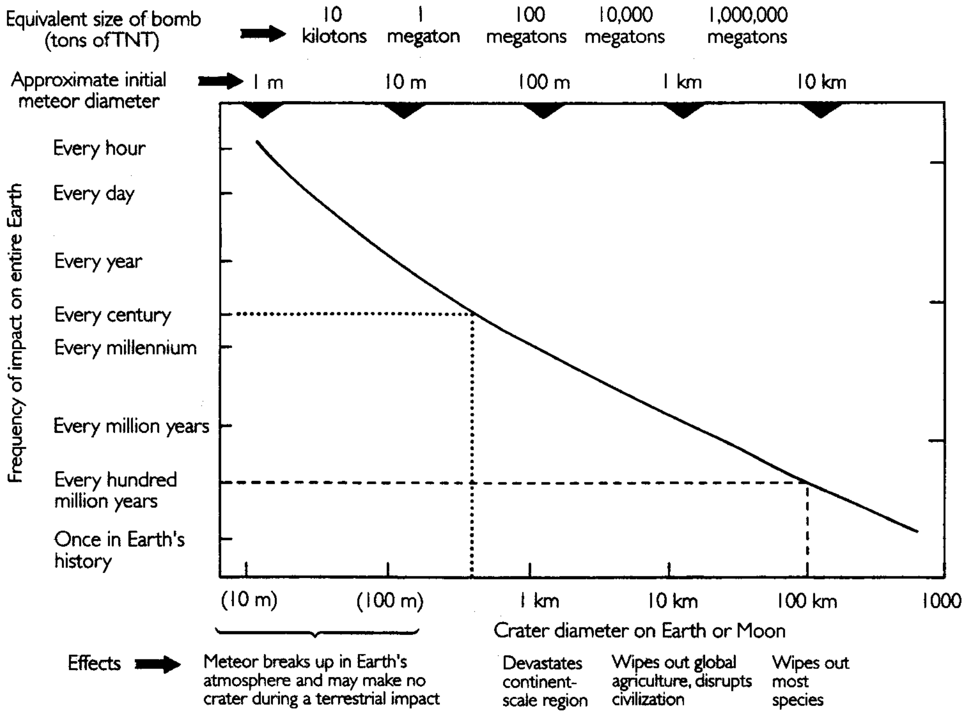

Figure 1. Rate of meteor impacts at the top of the Earth's atmosphere as a function of size. The dotted line shows the Tunguska Event of 1908. The dashed line shows the impact that wiped out the dinosaurs and other species 65 million years ago. This graphic is taken from Ward and Brownlee, 2000, page 165.

How many planets have had their biosphere destroyed by an untimely impact? How many other types of extinction-level events might exist? A nearby supernova or gamma ray burster could easily sterilize an entire solar system, much less a planet.

The Rare Earth factor f_{me} is used to account for the number of planets where the frequency of mass extinction events is below a minimum threshold value. In other words, planets that experience enough time between extinction events for live to evolve into complex forms.

Fraction Metal-Rich Planets (f_{pm})

The final factor included in the Rare Earth Equation is the fraction of planets that have a metal-rich composition. According to Ward and Brownlee, "planets that form around metal-poor stars may be too small to retains oceans, atmosphere, and plate tectonics (Ward & Brownlee, 2000)." Each of these consequences has serious consequences to the existence of complex organisms.

If there is not enough water to form oceans, it seems unlikely that the first single-celled organisms could have evolved, much less developed into complex metazoans. Without an atmosphere there would not be any mechanism for gas transport, nor would there be anything to protect the oceans from boiling away into the vacuum of space. Plate tectonics are though to be critical to the maintenance of the Carbon cycle and encouraging speciation (Ward & Brownlee, 2000). The actual fraction of metal-rich planets is not known, although it is reasonable to assume that this number is related to n_g, the number of stars in the galactic habitable zone.

Once all the factors in the Rare Earth Equation have been estimated or determined, a series of "what if" scenarios may be run to determine the likelihood of complex life existing on other planets. I turn to such an analysis in the next section.

Analysis

In this section, I analyze the definition of life, and examine the probability of actually detecting another life-bearing planet (assuming that all factors are non-zero). Finally, I propose how the two equations can be reconciled.

Must life be Earth-like?

One of the biggest differences between the REH and the work of SETI researchers such as Drake and Sagan hinges on the definition of life.

To Drake et al., the form life takes is not important. The only term in Drake's equation that even comes close to making a direct comparison to Earth is n_e, which is defined as the number of planets orbiting a star that are "ecologically suitable for life (Sagan, 1980)." This is usually interpreted to mean the region around a star where water can be found in its liquid state. But perhaps this is an unfounded assumption—how can we know for certain that liquid water is an absolute requirement for life? The REH goes even further and assumes that not only must the environment be Earth-like, but also that the history of a planet must be similar to Earth's in order for life to evolve. Why is this assumption made? It might be so that we can identify life if we find it, but at least one author believes that it is due to a so-called "creation scientist" who may have influenced Ward and Brownlee.

Ward and Brownlee spend chapter after chapter of their book explaining why it would be next to impossible for life to evolve exactly like it did here on Earth. They then come to the conclusion that complex life is exceedingly rare, perhaps even unique. They never consider the possibility that life might not need to be exactly like that found on Earth.

The year after *Rare Earth* was published, David Darling, an astronomer and noted science writer, published a book called *Life Everywhere: The Maverick Science of Astrobiology*. In it, he presents evidence that Ward and Brownlee were influenced by another astronomer that they had been in conversation with, Guillermo Gonzalez (Darling, 2001). Gonzalez is acknowledged by the authors in Rare Earth (Ward & Brownlee, 2000). In a later interview with *Salon* magazine, Darling stated:

> “I contacted Peter Ward and asked how much Gonzalez influenced him in the writing of the book. He replied, "He's been a major influence about the importance of some features of the earth that are unique to Earth and that we believe are important in the rise of complex life." I then said to him, "Did you know that Gonzalez writes extensively as a Christian apologist, defending the view of intelligent design?" And he said, "No, I had no idea of this. Are you sure?" Then he wrote to Gonzalez and asked for an explanation and Gonzalez said he wasn't making any apologies for the fact that his religious beliefs affect his science and vice versa (Hansen, 2001).”

Although the extent of Gonzalez’s influence on *Rare Earth* is not known, it certainly calls into question the rationale for using such a narrow definition of life in support of their hypothesis.

Statistics of Detection

One very important thing to remember is that the number of complex life-bearing planets in the galaxy is not directly proportional to the probability of finding them. Certain detection methods would provide unequivocal results; such as the detection of a radio broadcast originating from another solar system. However, after 40 years of SETI research, it seems more likely that life will be detected by observations of secondary indicators, such as free Oxygen in a planetary atmosphere (Ward & Brownlee, 2000). These secondary methods are not error free, so we must also evaluate the probability that any positive results are in fact correct.

Suppose that only 0.001 of all the planets in the Milky Way were known to harbor planets with complex life, despite the fact that we will not necessarily going to be able to detect whether each planet harbors life owing to measurement error, bad theory, instrument failure, and the like. However, assume that our hypothetical survey measurements have an accuracy of 95%. Call this accuracy factor the probability of correct classification p(C|L), which is 0.95.[4]

Using Bayes’ law, we can derive the probability that a planet classified as life-bearing really does harbor life:

$$p(L\,|\,C) = \frac{p(L)}{p(C)}\,p(C\,|\,L) = \frac{0.001}{0.05}(0.95) = 0.019 \qquad (3)$$

This produces the result that although the probability of correctly identifying a life-bearing planet is 19/20, the probability that an individual planet is really life-bearing (given that is was classified as life-bearing) is only 0.019.

---

[4] The nomenclature used here and in the following equations is explained in Appendix A.

Thus the effectiveness of the search strategy is critically important in determining how likely it is that for a given planet, it is correctly classified as life-bearing.

Adding It Up

If one accepts the Rare Earth Hypothesis, along with its possible faults, adjusting it so that it predicts the number of detectable civilizations (N_{DC}) is trivial, as shown in equation 4.

$$N_{DC} = N_{RareEarth} \bullet f_I \bullet f_C \bullet f_L \tag{4}$$

$N_{RareEarth}$ represents the predicted number of planets with complex metazoans. Three additional factors (borrowed from the Drake Equation) have been added. f_I is the fraction of those planets that develop intelligent life, f_C is the fraction of planets that develop a civilization capable of interstellar communication, and f_L is the fraction of a planet's existence representing the lifetime of a communicating civilization.

By adding these three factors to the Rare Earth Equation, one can see how infinitesimally small the chances are for SETI programs to succeed in detecting another civilization, especially if you include the Bayesian statistics of detection as illustrated in equation 3.

Conclusion: How Rare is Rare?

Estimates for the Drake Equation have ranged from early estimates of 10^3-10^9 in 1963 and dwindled down to 0.003 in 1981 (Dick, 1998). Newly discovered extrasolar planets will certainly result in the estimates increasing in value once again.

Although Ward and Brownlee presented the Rare Earth Equation in 2000, they declined to give an estimated value for N. Instead they simply state "that Earth indeed may be extraordinarily rare" (Ward & Brownlee, 2000).

To illustrate how truly unlikely it is that a SETI project will succeed, we will arbitrarily set the value for $N_{RareEarth}$ to 0.00003 (the most pessimistic estimate of the Drake equation, reduced by two orders of magnitude). Optimistically setting both fI and f_C to 0.1, and f_L to 0.00003 yields the following:

$$\begin{aligned} N_{DC} &= N_{RE} \bullet f_I \bullet f_C \bullet f_L \\ N_{DC} &= 0.00003 \bullet 0.1 \bullet 0.1 \bullet 0.00003 \\ N_{DC} &= 9x10^{-12} \end{aligned} \tag{5}$$

Recalling equation 3 and assuming that our search method is again 95% accurate, we can once again derive the probability that at a planet classified as life-bearing really does harbor life:

$$p(L \mid C) = \frac{p(L)}{p(C)} p(C \mid L) = \frac{9.0x10^{-12}}{0.05}(0.95) = 1.71x10^{-10} \tag{6}$$

9.0×10^{-12} is the probability that an intelligent civilization other than ours exists in our galaxy. Any “positive” detection has a probability of being correct of only 1.71×10^{-12}—rare indeed.

Further Research

It is obvious that further research needs to be conducted to determine accurate values for many terms in both the Drake and Rare Earth Equations. In particular, the fraction of stars with terrestrial planets capable of supporting life is critical. A number of new observatories are being proposed and built. In time this should help to provide a more concrete value for this factor. Strategies and technologies for detecting life from interstellar distances need to be developed and implemented. This is a field in which the potential research lifetime can be measured in centuries.

Summary

In this paper, I examined the Rare Earth Hypothesis (REH) as proposed by Ward (no relation) and Brownlee. In particular, I compared the Rare Earth Equation to the traditional Drake Equation and analyzed their similarities and differences.

A clear distinction was made between the objectives of the Drake Equation and the REH. A hybrid equation, based on both of them, was proposed. In addition, Bayes’ law used to compare the number of life-bearing worlds with the probability of correctly identifying such a world.

Regardless of the equation used, or the effectiveness of the search method utilized, it is indeed safe to conclude that our Earth is indeed rare. The knowledge of how rare intelligence seems to be in the universe only serves to remind us how precious it is and how important it is to preserve it.

Appendix A: Bayes' Law

Suppose there are two events (A) and (B) that are of interest. The conditional probability of A given that B has occurred is simply:

$$p(A \mid B) = \frac{p(A, B)}{p(B)}\,, \tag{1}$$

where $p(A,B)$ is the probability that both A and B occur, and $p(A|B)$ is the probability of event A given that event B has occurred.

Equation (1) is the probability of A after B occurs. We can also define a probability in which event A precedes B:

$$p(B \mid A) = \frac{p(B, A)}{p(A)} \tag{2}$$

Since, however, the probability that A and B occur is the same as the probability that B and A occur, it is possible to rearrange these two equations to show that:

$$p(A \mid B)\, p(B) = p(B \mid A)\, p(A) \tag{3}$$

or by rearranging further:

$$p(A \mid B) = \frac{p(A)}{p(B)}\, p(B \mid A)\,. \tag{4}$$

Equation (4) is known as Bayes' Law (Bayes, 1763; Jeffreys, 1998).

References

Bayes, T. (1763). An Essay towards Solving a Problem in the Doctrine of Chances. *Philosophical Transactions of the Royal Society of London, 53*, 370-418.

Crowe, M. J. (1986). *The Extraterrestrial Life Debate 1750-1900: The Idea of a Plurality of Worlds from Kant to Lowell.* Cambridge: Cambridge University Press.

Darling, D. J. (2001). *Life Everywhere : The Maverick Science of Astrobiology* (1st ed.). New York: Basic Books.

Dick, S. J. (1998). *Life on Other Worlds*. Cambridge: Cambridge University Press.

Ferris, T. (2002). *Seeing in the Dark.* New York: Simon & Schuster.

Gonzalez, G., Brownlee, D., & Ward, P. (2001). The Galactic Habitable Zone: Galactic Chemical Evolution. *Icarus, 152,* 185-200.

Greene, W. M. (2002a, 30 September). *Planet Quest: New Worlds Atlas.* Retrieved 13 October, 2002, from http://planetquest1.jpl.nasa.gov/atlas/atlas_index.cfm

Greene, W. M. (2002b, 17 September). *Planet Quest: News.* Retrieved 27 October, 2002, from http://planetquest.jpl.nasa.gov/news/tau1_gruis.html

Hansen, S. (2001, 29 June). *We've got company*. Retrieved 31 October, 2002, from http://archive.salon.com/books/int/2001/06/29/darling/print.html

Jeffreys, H. (1998). *The Theory of Probability* (3rd ed.). Oxford: Oxford University Press.

Jones, B. W., Sleep, P. N., & Chambers, J. E. (2001). The stability of the orbits of terrestrial planets in the habitable zones of known exoplanetary systems*Astronomy and Astrophysics, 366,* 254-262.

Sagan, C. (1980). *Cosmos* (1st. ed.). New York: Random House.

Shostak, S. (1998). *Sharing the Universe: Perspectives on Extraterrestrial Life.* Berkeley: Berkeley Hills Books.

Ward, P. D., & Brownlee, D. (2000). *Rare Earth: Why Complex Life Is Uncommon in the Universe.* New York: Copernicus.

Wetherill, G. W. (1994). Possible consequences of absence of Jupiters in planetary systems. *Astrophysics and Space Science, 212*, 23-32.

Wolszczan, A. (1991). Two Planets Around a 6.2-ms Pulsar 1257 + 12? *Bulletin of the American Astronomical Society, 23,* 1347.