

# **The Process of Evolution, Mass-Extinction Events, and the Lack of SETI Success**

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## **Abstract**

This paper will look at a model of species extinction wherein species evolve in bursts or “avalanches,” during which they become on average more susceptible to environmental stresses or external events and are, thus, much more susceptible to extinction events. Part of the goal of this paper is also to suggest one possible mechanism that might routinely cause such extinction events that also serves to drive evolution forward even as it destroys many species. Finally, the paper will look how this possible mechanism might, to a certain degree, explain the lack of current SETI success by adding another parameter to the famous Drake Equation.

## **I. Introduction**

Of all the species that have lived on the Earth since life first appeared here in the simplest form around three billion years ago, only about one in a thousand is still living today. All the others became extinct, typically within ten million years or so of their first appearance. This high extinction rate has had an important influence on the evolution of life on Earth: the population and repopulation of an ecological niche by species after species allows for the testing of a much wider range of survival strategies than the slower process of phyletic transformation by which a species gradually adapts to its surroundings. This, in turn, has contributed greatly to the diversity of life on the planet.

The importance of extinction to the development of life leads us to some crucial questions, the most fundamental of which is this: is extinction a natural part of the evolutionary process, or is it simply a chance result of occasional catastrophes besetting either single species (such as diseases) or larger groups of species (such as changes in the salinity of the sea, or changes in the climate) Many talented thinkers have offered arguments on either side of this debate (Raup, 1986; Smith, 1980).

In this paper I suggest that the truth lies somewhere between the two opposing points of view, and present a model demonstrating how the evolutionary process might interact with environmental stresses to produce a distribution of extinctions similar to that seen in the fossil record.

### **Bad Genes or Bad Luck?**

In his excellent account of extinctions in terrestrial prehistory, Raup (1991) has examined the question of whether extinction arises as a natural part of the evolution process. In his words, do species become extinct through “bad genes or bad luck?” By “bad genes” Raup means extinctions which occur because species are poorly adapted to their surroundings and so have low reproductive success. Recently, an interesting new mechanism for “bad genes” extinction has highlighted in the work of Bak and Sneppen (1993), where initially well-adapted species become less well-adapted if one or more of the other species with which they interact (for example by predation or by competition) evolve into some other form. Such a change of situation can force a species to evolve itself, with the ancestral species disappearing (a “pseudoextinction” in Raup's nomenclature), or it can eliminate a species altogether, leaving available for repopulation by another species the ecological niche that the species used to occupy. In the model proposed by Bak and Sneppen, these changes produce a “domino” effect in which the evolution of one species causes a number of others to evolve, and they affect others still, and there results an “avalanche” of evolution propagating through the ecosystem. They suggest that this mechanism alone could be sufficient to explain the mass extinctions seen in the fossil record; extinction could be a natural result of the way in which species evolve, and is not necessarily dependent on external physical factors.

There is another camp however, who point out that there are extinction events in the history of the earth which have known external causes (Raup and Boyajian, 1988), and therefore that the model of Bak and Sneppen is at best incomplete. To take the most

famous example, there is now a very convincing accumulation of evidence to suggest that the Cretaceous-Tertiary (K-T) boundary extinction was caused by the impact of a meteor or comet about ten kilometers in diameter on the Yucatan Peninsula in Mexico (Alvarez *et al.* 1980, Swisher *et al.* 1992, Glen 1994). Bak and Sneppen themselves make this point, stressing that the mechanism of their model is not the only one for extinction, but merely that, in the absence of other mechanisms, theirs might still give rise to mass extinction events.

In this paper I am going to propose a new model, similar in many respects to that of Bak and Sneppen, which combines the effects of bad genes and bad luck to make new predictions about the distribution of extinction sizes. The idea behind the model is that species undergo evolution in bursts, as in the model of Bak and Sneppen, and that during these bursts the species will on average be less resilient and well adapted to their environment than they are at other times. If an external stress is placed on the ecosystem during such a period of evolutionary activity, I therefore expect the extinction rate to be higher than it might have been if the same stress had occurred during a period of relative phenotypic stability. (This idea is not proposed here for the first time – a number of authors have suggested relatively similar mechanisms, e.g., Quinn and Signor (1989), Kauffman (1991, 1993), Plotnick and McKinney (1993).) From this simple hypothesis I have created a model that shows many features seen in the fossil record. I see sporadic bursts of evolution, which Bak and Sneppen have likened to the “punctuated equilibrium” behavior postulated for individual species by Eldredge and Gould (1977, 1993). I see a (power-law) distribution of extinction sizes ranging from “mass” extinctions wiping out a significant fraction of all species, to “background” ones wiping out just one or two species. I also see “precursor” extinctions in which species are seen to be slowly dying off for a certain period before a major extinction event, and “aftershocks” in which opportunistic, but not particularly well adapted, species are quickly extinguished as they rise up in the aftermath of a major event.

In Section II I will describe the model I am proposing in more detail. In Section III I will give the results of my simulations and analytic calculations on the model. In Section IV I explain a possible method of extinction events. In Section V I give my conclusions.

## **II. The Model**

My model is a generalization of the “minimal self-organized criticality” model for evolution of Bak and Sneppen (1993). I consider an ecosystem with a fixed number  $N$  of species or species groups, and for the purposes of the model characterize each by just two real numbers: a fitness and a barrier to mutation, denoted  $F_i$  and  $B_i$ , respectively for the  $i$ th species. I use the fitness as a measure of how susceptible a species is to extinction from environmental effects such as climate change, and not as a gauge of the relative merits of one species over another in direct competition between species. There is no mechanism within this model for direct inter-species competition. There is no absolute scale for the fitness measure. For convenience I have allowed the fitness measure to take values between zero and one.

The barrier to mutation is a measure of how far a species must mutate against a selection gradient (Caswell 1989) before reaching the domain of attraction of a new evolutionary stable phenotype. This concept is illustrated in Figure 1, which portrays a section of a “rugged fitness landscape” (Wright 1982, Kauffman 1993), in which different points on the horizontal axis represent different phenotypes, and the vertical axis measures, for example, lifetime reproductive success, or some other suitable measure of species success.

Species spend long periods of time at maxima in this landscape, where they are well adapted to their environment. Small mutations away from such a maximum are always driven back to the maximum again by the selection gradient. On very rare occasions a species will undergo a large mutation, or possibly a rapid succession of small ones, which will carry it so far from the current maximum that it passes one of the barriers into the domain of attraction of a different maximum. It will then be driven towards that new maximum by the selection gradient in that domain, and probably then remain there for some time, again undergoing small fluctuations about its new form. These phyletic jumps can set off a chain reaction of coevolution in other species, giving a burst or “avalanche” of evolutionary activity. My barrier variables are a primitive representation of the situation depicted in Figure 1, in which I take into account only the height of the smallest barrier a species needs to traverse in order to reach a new maximum in the fitness landscape. (For the phenotype indicated in the figure, this smallest barrier is shown as  $B$ .) Again there are no obvious units for the heights of the barriers, so, following Bak and Sneppen, I have chosen them to lie in the range between zero and one.

Initially I take my  $N$  species and assign to each a fitness and a barrier chosen at random within the allowed range. Then I consider how the ecosystem is likely to evolve. My simulation consists of the repetition, always in the same order, of three basic steps. The most likely event is that the species with the lowest barrier to mutation – call it species  $m$  – will evolve first. So the first step is to find that species and have it evolve into some new form characterized by a new value of the fitness  $F_m$  and a new barrier to mutation  $B_m$ , which again I have chosen at random within the allowed range. This process has the effect of removing the species with the lowest barriers from a population. The second step is to also choose new random values for the fitness and barrier height of  $K-1$  “neighbors” of species  $m$ . ( $K$  is defined in this way for compatibility with the “NK” models of Kauffman (1993) and others.) The neighbors are those species with which species  $m$  interacts in some fundamental way, for example by predation or by competition for resources. The neighbors can be chosen in a number of different ways. Here I follow Bak and Sneppen and make the simplest choice, whereby the neighbors of species  $m$  are selected at random from the  $N-1$  possible candidates. The changing of the fitnesses and barriers for the neighbors models the change in the environment of the neighboring species brought on by the change in species  $m$  which it undergoes when it evolves. It is this change in the parameters describing the neighbors that give rise to coevolutionary avalanches within this model, since it may well be that the new barrier to mutation chosen for one of the  $K-1$  neighbors will be low enough that it will be the next species that is chosen to evolve, precipitating a chain reaction.

The third and last step in my simulation mimics the effect of environmental forces on my model ecosystem. I imagine that environmental forces put some stress on the system which will cause some species to become extinct. Most of the time this stress will not be very severe and the majority of species will be unaffected. But occasionally there will be some larger event which will cause greater extinction. To model such processes I choose a random number  $r$  between zero and one at each step in the simulation. This number represents the stress being placed on the ecosystem by external forces. I then assume that all species whose fitnesses are less than this number become extinct at this time, and I replace their fitness and barrier parameters by new ones chosen at random, to represent the repopulation of their ecological niches by newly appearing species. I have experimented with a number of different forms for the random numbers (or “noise”) in my model, including Gaussian (white) noise,  $1/f$  noise, exponentially distributed random numbers, and bimodally distributed random numbers. The most important predictions of my model are independent of the form of the noise that I choose, implying that it is not necessary to know the exact nature or even the cause of the stresses placed on the ecosystem, or their distribution and frequency, in order for the model to make predictions about mass extinction. Most of the results presented here are for Gaussian noise centered at zero with a standard deviation which I denote  $\sigma$ . In the limit  $\sigma = 0$  in which the noise vanishes, the fitness parameters no longer have any effect on the model, since no species ever have a low enough fitness to get wiped out. In this case my model becomes the same as that of Bak and Sneppen. In most of simulations, I have kept the noise level quite small, with typical values for  $\sigma$  being around 0.1 or 0.2.

My simulations consist of repeating the above processes – evolution of the species with the lowest barrier to mutation, changing of the fitnesses and barriers of its neighbors, extinction of the species with the lowest fitnesses – many times over (typically about  $1000N$  times) and examining the resulting pattern of extinctions, the distribution of extinction sizes, and the distributions of fitnesses and barriers to mutation.

### III. Results and Discussion

I have performed simulations of my model for up to  $N = 10,000$  species and up to ten million time-steps. (I have not said how long an interval of geological time my time-step corresponds to, but none of the results presented below depend on knowing this. In theory it may be possible to answer this question by comparison of fossil data on species lifetimes with similar data extracted from the simulation. However, for this current work I have not attempted to perform this comparison.)

My simple model where each species interacts with  $K-1$  others is only an approximation to the behavior of a real ecosystem; real species can interact with other species strongly or weakly, and different species will interact with different numbers of neighbors. Neither of these effects is allowed for in this simple model. However, if one is to choose a single figure for the number of neighbors for a simulation such as this, then experimental data (for example, the work of Sugihara, Schoenly, and Trombla (1989) on analysis of food webs) suggest a value of 3 or 4. The results presented here are for three neighbors ( $K = 4$ ). Figures 2 and 3 show the distributions of fitnesses and barriers for two different strengths of the external noise. The individual symbols are the values calculated from my

simulations. The lines running through them are the values of the same quantities calculated from an analytic “mean field” solution of the model. This mean field solution is a generalization of the one given for the model of Bak and Sneppen.

The technical details of the solution will be covered in another paper that I am planning on writing. For the moment I simply note that the mean-field solution agrees excellently with the simulation results. This allows me to probe the behavior of the model in regimes in which the statistics from the simulations are less good, and also in theory to extract exact results for certain quantities appearing in the model, such as the exponent  $\alpha$  defined in Equation 1 that will be shown later in this paper.

The distribution of fitnesses shows essentially the behavior I would expect of it: the external stresses placed on the system remove species with low fitness, so that the distribution has most of its weight in the upper half of the range. Towards the top of the range, where noise events large enough to wipe out the species are rare, there is no practical difference between species with different fitnesses, so the distribution is flat. In the limit where the fitness  $F \rightarrow 0$  no species can survive, since there is some small finite noise level present at every step in the simulation, so the distribution is guaranteed to tend to zero in this limit. The barrier distribution also tends to zero as barrier height tends to zero, since an infinitesimal barrier is extremely likely to be the lowest one in the ecosystem, causing the corresponding species to evolve to a new form with a different barrier to mutation. In the limit of large barriers, the distribution is again constant, since a large barrier is very unlikely to be the lowest one and there is then no practical distinction between the species at the high end of the distribution.

Figure 4 shows a plot of the extinctions occurring in a population of 10,000 species against time. There are long periods during which there is little activity – a few species dying out here and there, but nothing particularly catastrophic – followed by a few large extinction events, followed by a further period of relative inactivity, and so forth. To understand the mechanism through which this behavior arises within the model, consider the behavior of species’ fitnesses as time goes by. Starting with a well-adapted ecosystem in which the bulk of the species have a high fitness (tolerance to external influences), I allow my process of evolving the species with the lowest barrier to proceed for a while. At each time-step this replaces  $K$  species with new ones with randomly chosen barriers and fitnesses. There is a reasonable chance that these fitnesses will not be as high as those of the well-adapted species from which these new ones have evolved, and so these species may be wiped out by quite small environmental stresses. These are the small extinctions that can be seen going on most of the time in Figure 4.

In fact, the evolutionary process will proceed, as described in Section II, in coevolutionary avalanches, most of which will be small. However, as shown by Bak and Sneppen (1993) there is a power-law distribution of these avalanches, and occasionally large ones occur. When this happens, a large number of species have their fitnesses changed to new random values, and consequently a large number become more susceptible to external factors. As long as the noise level remains low, this is not a problem, but if a particularly large noise event occurs, then a significant fraction of these

species can be wiped out, giving rise to the large extinction events seen in the data. The important point here is that large extinctions arise as a result of the coincidence of catastrophic environmental changes with large coevolutionary avalanches, during which the susceptibility of large numbers of species to external effects is increased.

There are many indicators in my simulation results that this is the correct explanation of the observed distribution of extinctions. For instance, I have calculated the fraction of the species which have fitness below a certain threshold immediately before each avalanche (in the present case we took that threshold to be twice the noise level), and then taken the average of this quantity for each size of avalanche. The results of this calculation are shown in Figure 5, and it is clear that the fraction of species with low fitnesses increases before a large avalanche. Large extinctions are therefore not just an effect of large environmental changes. Another important indication is shown in Figure 6, which is a logarithmic histogram of the size of extinctions against the frequency of occurrence.

The first thing that can be noticed is that the graph goes steeply downwards, indicating that large extinctions are much less common than small ones. It is also noticeable that on this plot the distribution falls on a straight line for most of its range, indicating that the extinction distribution is a power law. In fact I find that the frequency of an extinction  $P(s)$  is related to its size  $s$  by

$$P(s) \propto s^{-\alpha} \quad (1)$$

where

$$\alpha = 2.183 \pm 0.007$$

Bak and Sneppen find a power-law distribution for the coevolutionary avalanches in their model, but with an exponent different from the one found here. They equate their avalanches with extinctions, but I suggest that the avalanches, while being a crucial part of the mechanism giving rise to mass extinction, do not themselves represent actual extinctions. In fact, I would expect that my exponent  $\alpha$  describing the distribution of extinctions to be greater than the exponent found by Bak and Sneppen for the avalanches. The reason is that I require the coincidence of two unlikely events – environmental catastrophe and a large coevolutionary avalanche – to produce a large extinction event. Merely having a large avalanche is insufficient; large avalanches take place without giving rise to large extinctions because the environmental conditions are not right for extinction. Thus we expect large extinctions to be relatively less common than large avalanches, and so I expect my power-law distribution to be steeper than that for the avalanches. This is in fact what I observe, since Bak and Sneppen find a value of 1.35 for the exponent governing their power-law distribution, which is considerably less than my 2.18.

The form of the power-law distribution is one of the most robust predictions of my model. I have run the model with a variety of different types of noise, with different numbers of neighbors  $K$ , and with a number of variations in the precise dynamics of the

model, all without changing the value of the exponent  $\alpha$  in Eq. (1). Thus it is not necessary to know exactly what external effects are responsible for the mass extinctions, or what their distribution is over time – it makes no difference to this particular prediction. This is an important observation since it should, in theory, be possible to check this prediction against paleontological data, for example in the fossil data of Sepkoski (1993) or even of Williamson's (1981) earlier work. Another telling form of behavior seen in my model is the generation of smaller extinctions that accompany the largest ones. These fall into two classes.

*Precursors* is the name given to sets of small extinctions which precede a large extinction. Such precursor extinctions are to be seen all over the data from my simulations. Figure 7a shows a set of precursor extinctions drawn from the data shown in Figure 4. The explanation of this effect is as follows: large extinctions are produced when a large portion of the population becomes less fit than the average following one or more large coevolutionary avalanches. After such an avalanche, the next large environmental stress placed on the system (if there is one before the species involved manage to evolve to a fitter state) will decimate the population. However, there may be a considerable interval of time before such a large stress occurs, and in the meantime, there may be smaller stresses which, because of the general unfitness of the population, tend to exact more of a toll on the ecosystem than one would normally observe. It is this exaggeration of the effect of small environmental changes in the interval following a large avalanche but preceding the next large noise event that we see in our data as precursor extinctions. It is interesting to note that precursor extinctions are seen in the fossil record also. The mass-extinction which occurred at the K-T boundary 65 million years ago was preceded by about three million years during which many species on the planet were already dying out (Keller 1989). The K-T boundary extinction is thought to have been caused by the impact of a large comet or meteor at Chicxulub on the Yucatan Peninsula, and this event corresponds to the "large noise event" in my theory. However, a comet cannot explain why species were dying out for three million years before, and it has been suggested (for instance, by Kauffman 1993) that these precursor extinctions might be a result of smaller environmental stresses on a population which become unfit for some other reason. This same unfitness would also go some way to explaining why the population of the planet was so severely reduced by the Chicxulub meteor. It is interesting therefore to observe the exact same effect appearing in my model, with the unfitness here being caused by large coevolutionary avalanches.

The name *aftershocks* is given to larger-than-normal extinctions that arise in the wake of a significant mass extinction. The mechanism here is that a large extinction wipes out a significant number of species, leaving empty many ecological niches. These niches are soon filled by new species. However, these species may not be very well adapted to survive new environmental stresses since they have not evolved for long enough to feel the selection pressure of those stresses. Thus many of them will quickly be wiped out by quite small noise events, which normally would have little effect on a well-adapted population. Only with the passage of time can the less fit species be removed from the population and the general fitness increase to normal levels again. Thus I would expect to see a series of moderate-sized extinction events appearing in the immediate wake of a



large event, dying away in size until we return to the normal spectrum of small extinctions. Figure 7b shows just such a set of aftershocks, also drawn from the data shown in Figure 4. Again, an effect similar to the aftershock seen in these simulations appears to be present in the fossil record. For example, during the well-known Precambrian explosion of six hundred million years ago, a large number of species, many with rather bizarre and ill-adapted morphologies arose very quickly in all sorts of different ecological niches. Most of these were wiped out rather quickly, many probably because they were not well able to cope with small changes in their environment. Thus extinction, as well as speciation, appears to have been at a maximum during this period. It is interesting to see this effect duplicated in my simulations.

As a last comment on my results, I would like to point that, although I have experimented with a large variety of different types of noise, to mimic different distributions of external influences, and found essentially the same predictions for the parameters of the system for all of them, there is one important respect in which all of these noise distributions were the same: they were all essentially similar at all points in time. It has been suggested (Raup and Sepkoski 1984; Sepkoski 1990) that there could be some periodicity in the largest of the mass extinctions seen in the Earth's fossil record, caused perhaps by the periodic recurrence of some astronomic catastrophe such as a meteor impact. I have performed simulations of my model which mimic this effect by introducing periodic variation in the strength of the noise function. The resulting extinctions show clear peaks at regular intervals, some more pronounced than others, in a fashion qualitatively similar to the peaks seen at twenty-six million year intervals in the fossil data. This does not of course prove that there is an external cause for any periodicity that may be present in the fossil extinction data; it merely demonstrates that, within my model at least, such external causes can produce periodicity.

#### **IV. A Periodic Extinction Method**

I have mentioned in the preceding pages the idea of punctuated equilibrium. Geologic crisis periods are what make up the major brunt of the theory of punctuated equilibrium. One problem is that theory, overall, does postulate that evolutionary advances occur during these periods, but it does not account for what those actual crises are or what accounts for them. Nor does it suggest if these crises are necessary for evolution to be a viable mechanism. In general, the majority of extinctions have no known cause. It is possible that some of them were the result not of environmental disasters but simply of natural evolutionary processes. However, it is known that many must have been caused by massive changes in the environment. I have also mentioned one aspect of extinctions as that of a comet or meteor impacting upon the Earth and the possibility of a periodicity in the extinction fossil record.

What I propose here is that comet/meteor impacts are a relatively periodic affair and that these events might come during those periods of relative instability when evolutionary "avalanches" occur. I also propose that these events may be, in fact, what helps to drive evolution forward to some degree even while wiping out large portions of the biosphere. It should be noted that I am certainly not the first to suggest a periodic nature to impact events. In fact, as I briefly mentioned in the last section the fossil data does, by some

interpretations, seem to indicate a periodicity of twenty-six and twenty-eight million years. Is there, in fact, such a periodicity? The idea has been put forth in relation to another star (called “Nemesis” or “Death Star”) that is a binary partner to our Sun or a rogue planet (called “Shiva,” not to be confused with a supposed inner planet called “Vulcan” or an outer planet called “Persephone”). This pattern has been found to be spurious for the most part, at least in terms of another star or rogue planet, although the average between massively big crises does seem to be between twenty and thirty-two million years.

Like the impact event periodicity, I am also not the first to put forth the idea that periodic extinction events may drive evolution to some degree. This was also put forth by Cramer (1986). The idea has to do with the existence of Jupiter and its effects on cometary and steroidal bodies in the solar system. There is an asteroid belt between Mars and Jupiter. At regions of about 2.5, 2.8, and 3.3 astronomical units from the Sun, there are gaps where there are no asteroids at all. (If we picture the asteroid belt like various rings, the gaps are areas of a ring that is empty.) The presence of these gaps might like a very odd phenomenon but according to astronomers these gaps exist because of the presence of Jupiter and its large mass. Specifically, it is due to the gravitational pull of Jupiter, which produces orbital deflections on entities around it and those deflections are gradually cumulative. These zones of relative emptiness are known as *Kirkwood gaps*. As Cramer says, these gaps “correspond to distances where there are orbital resonance’s because the ratio of the asteroid’s orbital period to Jupiter’s is 1:3, 2:5, or 1:2, respectively.” These gaps can act as a sort of slingshot for any object that gets into them because the effect of Jupiter’s massive gravitational pull is to create a zone that is hypersensitive to small variations in orbital parameters. Jupiter’s perturbative effects are more than a small variation. What this means is that the objects in the first Kirkwood gap would circle the Sun in a time which is just 1/3 of the 11.9 year orbital period of Jupiter. In other words, every third time an object in this orbit comes back to the same position, Jupiter is also in the same position and kicks the same way with its gravitational field. These repeated “kicks” in the same direction accumulate and make the orbit of the object being kicked unstable. (This is referred to by the technical name of the *3:1 resonance*.) These are also called chaotic orbits. It is proposed that the major impact events come from the Kirkwood gaps being disrupted. This causes potential crisis events on Earth when the bodies from the asteroid belt hurtle towards the inner solar system.

The idea, of course, is that this perturbation effect causes crisis events that could lead to extinction level events of various degrees. However, we have to consider that this effect is not totally random insofar as the fossil record of Earth would seem to indicate. And this would seem to be important. If the crisis events were to come too fast, the catastrophes would occur too often and would be too wasteful of life, too likely to extinguish too many species. We can also make the assumption that if the crisis events came too quickly on the heels of the previous ones that the species would not be able to fully adapt to the new ecological niches before the next cycle. Thus, overall, evolution would proceed much more slowly. (Interestingly, this would seem to be the case before the Precambrian explosion.) However, if the time between the crisis events is too long (meaning the periodicity is too slow) then the rate of evolution (by crisis-stimulation)

would be slowed as well and species might become too entrenched in niches such that they all die out rather than adapt when that niche is finally disrupted. One thing we have to consider about this of course is that it is not known if such perturbations happen periodically and, if they do, what mechanism would cause that to be so. We have to consider that this idea would seem to suggest some sort of “ideal” crisis/catastrophe rate. All of these are concepts for further research that will not be considered in this paper.

However, it is interesting to at least consider one other aspect of this idea of a sort of “pump” of evolution, to use Cramer’s term. Could this concept affect other life in other star systems? Could it, in fact, offer one possible explanation for the current lack of SETI (Search for Extra-Terrestrial Intelligence) success? A lot of what drives the search for extraterrestrial intelligence is the idea of the Drake Equation, an equation put forth by Frank Drake in 1961 as a way to focus on specific factors that might determine how many intelligent and communicating civilizations that exist in our galaxy. The equation is given as such:

$$N = N^* f_p n_e f_l f_i f_c f_L \quad (2)$$

Here  $N^*$  represents the number of stars in our galaxy,  $f_p$  is the fraction of stars that have planets around them,  $n_e$  is the number of planets per star that are capable of sustaining life,  $f_l$  is the fraction of planets in  $n_e$  where life evolves,  $f_i$  is the fraction of  $f_l$  where intelligent life evolves,  $f_c$  is the fraction of  $f_i$  that communicate, and  $f_L$  is the fraction of a planet’s life during which the communicating civilizations live. The end result,  $N$ , is the number of communicating civilizations in the galaxy. It should be noted, of course, that there is a staggering amount of guesswork and assumption that currently goes into the values of these various parameters. What is important to consider at this point is that the type of crisis/catastrophe evolution that I have been talking about here would most likely have the effect of greatly reducing the  $f_i$  parameter of the Drake Equation. However, if this type of evolution were, to some degree, necessary for the type of evolution we have seen (that leads to an intelligent, communicating civilization) we can even consider adding another parameter to the Drake Equation, say  $f_{cc}$ , for the fraction of  $f_l$  where there is a type of crisis/catastrophe “pump.” Notice that this is a fraction of  $f_l$ , which is the fraction of planets where life evolves in general and is not a consideration of intelligent life. This is because the crisis/catastrophe “pump” would affect life at all times during the course of evolution, not just when it was intelligent.

So could this idea of a crisis/catastrophe rate explain a possible mechanism that life needs to evolve to the degree where it can form intelligence (or, perhaps, just highly advanced life)? Could this be a parameter that explains the current lack of SETI success? Could this put a sort of constraint on the number of civilizations that may evolve in our galaxy? For that to be the case, it would require a lot of a given solar system. It would require the basic mass of the Sun, the orbital radius of an earthlike planet, the mass and orbit of a giant Jovian planet, the presence of an asteroid belt with just the right range of orbits and densities. Not only might this pump mechanism be unlikely elsewhere but the timings might be as well. We would also have to assume that evolution would work in the same

manner on other planets and with other species. In any event, these are not areas that will be covered in this paper.

## V. Conclusions

I consider a mechanism whereby extinctions might arise as the result of the coincidence of coevolutionary avalanches giving rise to low general fitness of species in an ecosystem, and environmental stresses which tend to wipe out the least fit species. I have given a simple mathematical model which mimics this behavior and makes a number of predictions about the resulting distribution of extinctions. In particular, the extinctions appear to have a power-law distribution with an exponent independent of the precise form of the external stresses. This prediction should be testable against paleontological data. I also propose, more as an afterthought, a possible crisis/catastrophe parameter that might go some ways towards explaining the external crisis events that occur during periods of evolutionary “avalanches.”

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