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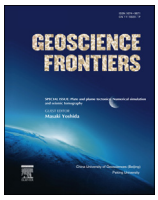

Research paper

United theory of biological evolution: Disaster-forced evolution through Supernova, radioactive ash fall-outs, genome instability, and mass extinctions

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ABSTRACT

We present the disaster-forced biological evolution model as a general framework that includes Darwinian "phylogenic gradualism", Eldredge-Gould's "punctuated equilibrium", mass extinctions, and allopatric, parapatric, and sympatric speciation. It describes how reproductive isolation of organisms is established through global disasters due to supernova encounters and local disasters due to radioactive volcanic ash fall-outs by continental alkaline volcanism. Our new evolution model uniquely highlights three major factors of disaster-forced speciation: enhanced mutation rate by higher natural radiation level, smaller population size, and shrunken habitat size (i.e., isolation among the individual populations). We developed a mathematical model describing speciation of a half-isolated group from a parental group, taking into account the population size (N_e), immigration rate (m), and mutation rate (μ). The model gives a quantitative estimate of the speciation, which is consistent with the observations of speciation speed. For example, the speciation takes at least 10^5 generations, if mutation rate is less than 10^{-3} per generation per individual. This result is consistent with the previous studies, in which μ is assumed to be 10^{-3}–10^{-5}. On the other hand, the speciation is much faster (less than 10^5 generations) for the case that μ is as large as 0.1 in parapatric conditions ($m < \mu$). Even a sympatric ($m \sim 1$) speciation can occur within 10^3 generations, if mutation rate is very high ($\mu \sim 1$ mutation per individual per generation), and if $N_e < 20$–30. Such a high mutation rate is possible during global disasters due to supernova encounters and local disasters due to radioactive ash fall-outs. They raise natural radiation level by a factor of 100–1000. Such rapid speciation events can also contribute to macro-evolution during mass extinction events, such as observed during the Cambrian explosion of biodiversity. A similar rapid speciation (though in a much smaller scale) also has been undergoing in cichlid fishes and great African apes in the last several tens of thousand years in the current African rift valley, including the origin of humankind due to the radioactive ash fall-outs by continental alkaline volcanism.

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1. Introduction

Charles Darwin (1859) argued that species evolve gradually through a large number of small changes by mutations, through "natural selection". Though paleontologists such as Cuvier (1831) reported many examples of new species suddenly appearing in fossil records, Darwin and his successors did not believe such sudden appearances of new species; they thought that such appearances are not real but artifacts due to the difficulties of reconstructing the emerging processes of new species due to imperfect fossil records.

This idea of evolution, so called "phylogenic gradualism", has been challenged by many researchers. First, Simpson (1945) studied the evolution of fossil horses in the middle west of the North American continent and found that their evolutional behavior was not one-directional but rather a complex network. He also argued

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the speed of evolution or speciation rate is considerably different depending on periods and places. In order to explain apparent changes in both speed and mode of biological evolution at a fixed point, Eldredge and Gould (1972) evaluated fossil records using the accumulated descriptions over 100 years after Darwin (1859) and recognized mass extinctions. They proposed a punctuated equilibrium model of evolution of species against the traditional idea of evolution. Though they postulated homeostasis or stability of existing species, detailed and qualitative analyses unfortunately have not yet been undertaken.

Dobzhansky (1937) stressed the importance of "reproductive isolation mechanism" that prevents gene flow among taxa. He believed that the speciation requires the build-up of the reproductive isolation, which led to the biological species concept: "identified species as grouped of interbreeding populations that are reproductively isolated from other groups" (Mayr, 1942). We adopted this biological-species concept in the present paper, so that speciation is nearly equal to the establishment of reproductive isolation.

Speciation rate through the history of the Earth is found to be correlated to mass extinction events, discovered by Raup and Sepkoski (1982), who compiled the fossil data and applied statistical methods to them. Sepkoski (1998) estimated global speciation rate on the Earth during the last 488 Ma, finding it to fluctuate at times. More recently, Bambach (2006) incorporated more mass-extinction information into the calculations. There are two peaks, followed by exponential decreases in the Cambrian Period and the post P/T mass extinction event. Moreover, eight or more mass extinctions are recorded prior to the Cambrian explosion at ca. 500 Ma, i.e., from Cryogenian to Cambrian through Ediacaran time (Shu, 2008), though it needs to be verified in locations other than China. Importance of the Ediacaran/Cambrian was pointed out by Gould (1989), who argued that all the extant animal phyla or the crown group of metazoan appeared in only 70 Myr, during the so-called Cambrian explosion, while any new phyla have not appeared until present-day, or for more than 500 Myr. Recent works by Shu (2008) and Shu et al. (2014) suggested that the explosion took place in a much shorter period, within 20 Myrs (540–520 Ma).

The speed of speciation of a population is believed to be related to four parameters: (1) the population size, (2) the degree of isolation, (3) mutation rate, and (4) the strength of selection. Firstly, many researchers believe that a more rapid evolution would occur in a larger population, since the total number of mutations in the group in a fixed time span would be greater for a larger population. In contrast, Mayr (1942, 1947, 1954) and his followers stressed the striking difference between the parental population and many peripherally isolated founder populations and species. This evidence was supported by the findings of Carson (1970) on incipient species and neospecies of Drosophila in Hawaii. Ohno (1970) also pointed out that evolutional speed is inversely proportional to the effective number, N_e, of the population that effectively exchange genome with each other; in fact, neutral mutation theory actually predicts that the evolutional timescale is inversely proportional to N_e, if the time of fixation of the mutation in the group is taken into account, particularly in the case of $4N_e\mu > 1$ (Kimura and Ohta, 1969; Kimura, 1970; Narain, 1970), where μ is the mutation rate per individual per generation.

Second, the degree of isolation of the population strongly influences the speciation process in a parapatric situation. Since the immigrants will supply the ancestral alle to the population, the genomic distance to the parental population remains relatively short due to immigration. Kimura and Weiss (1964) developed the stepping-stone model to investigate the effect of migration on the local differentiation of geographical barriers among the half-isolated habitats; they found that the immigration rate must be smaller than the mutation rate in order to accumulate mutation in a population.

Third, the mutation rate also influences the speed of evolution and speciation rate. Though researchers of evolution generally assume the mutation rate to be constant thus far, it may change by a significant factor depending on the time, place, and exposure to extraordinary environmental conditions. Encounters with supernova remnants (SNR), for example, can enhance the cosmic-ray flux by a factor of 100–1000 on the surface of Earth (Kataoka et al., 2013). Another significant example unfolded here are volcanic ashes from the eruptions of continental alkaline magma, which are sometimes highly enriched in radioactive elements such as ^{40}K, ^{235}U, and ^{232}Th. A series of eruptions can discharge radioactivity of 10^{16}–10^{18} Bq, which is comparable to that of the 1986 and 2011 nuclear power plant accidents of Chernobyl, Russia, and Fukushima Daiichi, Japan, respectively. In both examples, the enhanced levels of radiation dosage cause genome instability, which is accumulated across generations probably through epigenetic effects (e.g. Dubrova, 2006; Ryabokon and Goncharova, 2006; Aghajanyan et al., 2011).

Finally, the strength of natural selection is an important factor of evolution. In fact, Kimura (1957) found that the fixation probability of a mutation is strongly enhanced if it has a selective advantage in the local environment, including few advantageous mutations which may lead rapid morphological changes. It is, however, uncertain that the strength of selection enhances the speed of speciation (or establishment of reproductive isolation) in a realistic situation, since most of mutants are deleterious, whereas an advantageous one is quite rare in general.

Going beyond Charles Darwin and present-day perspective of biological evolution, we present a new disaster-forced biological evolution model, including how it addresses speciation perturbation on Earth. We construct a simple mathematical model of genetic divergence of a small peripheral group taking into account a finite population size, immigration, and mutation. We also assume that most of the mutations are neutral and advantageous mutation is rare.

We find that the new model explains a variation in the evolutional speed or speciation rate in time and place through catastrophic environmental changes. The evolution of the species is accelerated by environmental disasters in which the decrease in population size, the shrinkage of habitats of species, and the increase in mutation rate simultaneously take place through global environmental disasters. Here, two prime disaster-forced, speciation events are unfolded: supernova encounters and radioactive ash fall-outs by the rift-controlled volcanic eruptions of continental alkaline magmas. We found that speciation can be well explained in terms of a bifurcation employing the catastrophe theory originated through the works of the French mathematician René Frédéric Thom in 1960 (e.g. Zeeman, 1976).

The aim of the present paper is to give a theoretical framework of the biological evolution to promote quantitative studies and discussions, based on the disaster-forced evolution model. In Section 2, we present a simple model of the speciation of a half-isolated group from a parental group, taking into account the population size, the degree of isolation, and the mutation rate. Next, we discuss an environmental disaster caused by a supernova-remnant encounter in Section 3, and by a local disaster triggered by radioactive ash fall-outs from volcanic eruptions of continental alkaline magmas in Section 4, which includes comparing present-day speciation records with past speciation records along a rift zone. In the final section, we summarize our results and propose comprehensive studies of a rift zone and a nuclear power plant both influenced by high dosages of radiation to collect evidences of the disaster-forced evolution model.

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