Disaster-forced Evolution Model: Supernova, Carbonatite Volcanism, Genome Instability, and Mass Extinctions

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We present a new disaster-forced biological evolution model as a general framework that includes Darwinian “phylogenic graduation” (Darwin 1859), as well as Eldredge-Gould’s “punctuated equilibrium”(Eldrigdge and Gould 1972), mass extinctions, and aro-, para-, a nd sympatric speciation. It describes how reproductive isolation of organisms is established through global disasters due to supernova encounters and local disasters due to carbonatite volcanism. Our new evolution model uniquely highlights three major factors of disaster-forced speciation (referred to as speciation-forcings): (1) enhanced mutation rate by higher natural radiation level caused by supernova encounters or carbonatite volcanism, (2) smaller population size, (3) and shrunken habitat size (i.e., isolation among the individual populations; Figure 2).

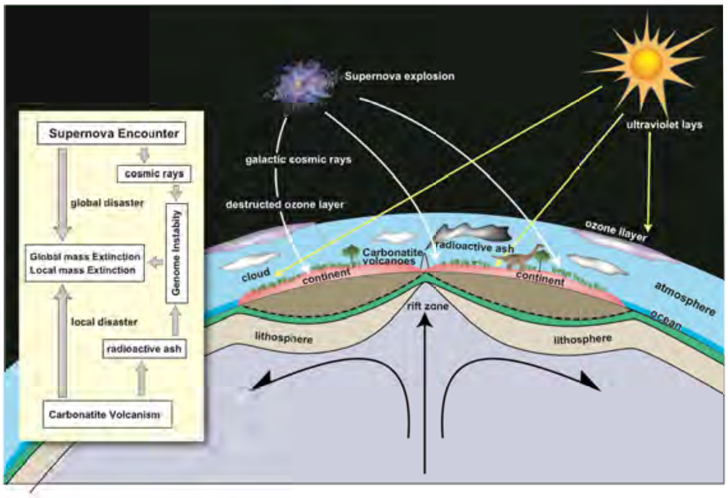

Figure 1. The concept of the disaster-forced evolution. A global disaster by supernova encounter and a local disaster by carbonatite volcanism force biological organisms evolve.

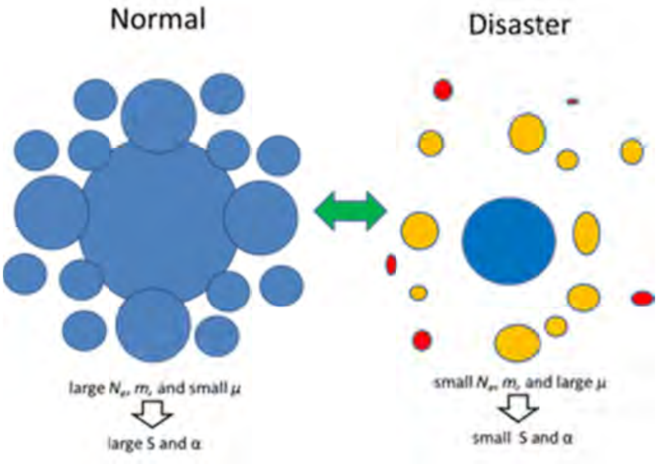

Figure 2. Schematic diagram showing a disaster-forced change, including a reduction in the total number and size of individual habitats. Note that small sub-populations in the peripheral region of their habitat become more isolated (yellow), even endangered (red).

We developed a simple mathematical model describing speciation of a half-isolated (peripheral) group from a parental group, taking into account the population size, N_e, immigration rate, m, and mutation rate, μ. 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 (Zeeman 1976; Figure 3).

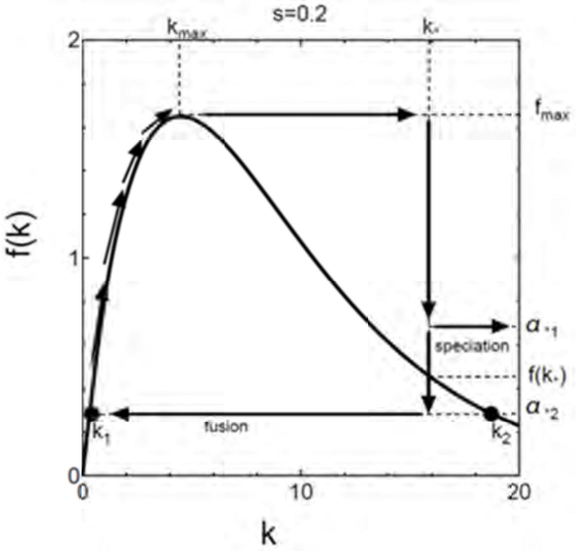

Figure 3. The region above the solid curve (speciation region), the solid curve, k always increases, while it decreases bellow the curve (refusion region). When a disaster starts, α=2μ/m increase, since μ increases because of the enhanced natural radiation level and/or m decreases because of the shrink of their habitats

The genomic distance, $\boldsymbol{k}$, between peripheral group from parental group is governed by an ordinal differential equation: $\boldsymbol{dk/dt = m\kappa(\alpha - f(k))/2}$, where $\boldsymbol{\kappa}$ is the fixation efficiency of mutations. When a parameter $\boldsymbol{\alpha = 2\mu/m}$ is smaller than a critical value, the maximum of the function $\boldsymbol{f(k)}$, a stable equilibrium ($\boldsymbol{dk/d\mathrm{t} = 0}$) solution of $\boldsymbol{k_1}$ exists, and the group remains subspecies or races interbreedable with the parental group. However, when $\boldsymbol{\alpha}$ exceeds the critical value, the stable equilibrium solution disappears and a runaway increase in $\boldsymbol{k}$ occurs: the genomic distance becomes eventually so large that reproductive isolation is significant between them. The model gives a quantitative estimate of the speciation speed, which turns out to fit well with the observations of speciation speed (Figure 4). For example, the speciation takes a least 10^5 generations, if mutation rate is less than 10^{-3}. This result is consistent with the previous studies, in which $\boldsymbol{\mu}$ is assumed to be $\boldsymbol{10^{-3} - 10^{-5}}$ per generation per individual. On the other hand, the speciation is much faster (considerably less than 10^5 generations) for the case that $\boldsymbol{\mu}$ is as large as 0.1 for the case involving parapatric conditions if $\boldsymbol{m < \mu}$. Even a sympatric $(\boldsymbol{m{\sim}1})$ speciation can take place within 10^3 generations, if mutation rate is very high ($\boldsymbol{\mu{\sim}1}$ mutation per individual per generation), and effective population is less than 20-30. Such a high mutation rate is possible during global disasters due to supernova encounters (Figure 5) and local disasters due to carbonatite volcanism (Figure 6).

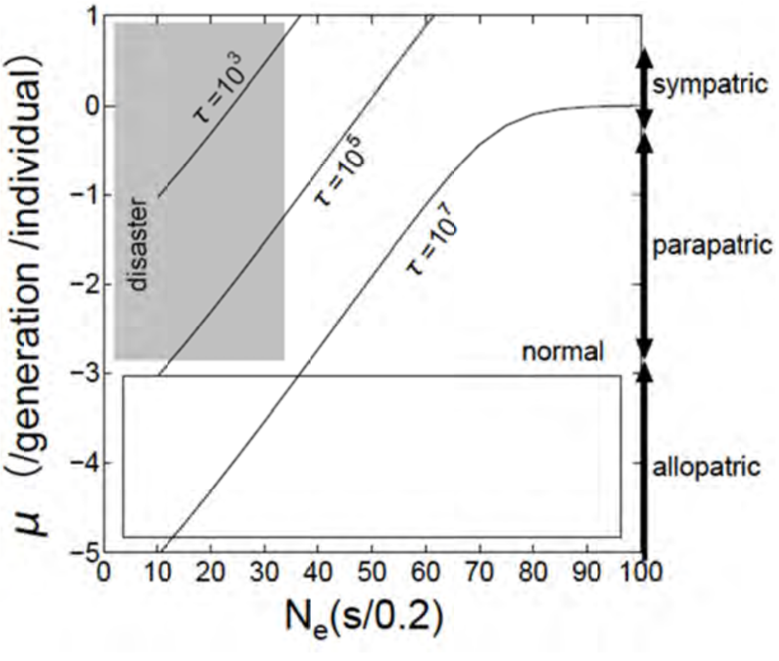

Figure 4. Conditions necessary to establish reproductive isolation (RI) are shown for the case where $\boldsymbol{s = 0.2}$ and $\boldsymbol{\xi s^* = 10^{-6}}$ in $\boldsymbol{\mu}$-$\boldsymbol{S}$ plane.

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 (Figure 7). A similar rapid speciation (though is in a much smaller scale) also has been undergoing in cichlid fishes and great African apes in the last several tens of thousands of years in the current African rift valley, including the origin of humankind, by nebular-encounter and carbonatite-volcanism speciation-forcings (Figure 8 and 9).

The new disaster-forced biological evolution model unites various concepts of evolution as follows. First, the phylogenic graduation can be placed in the case that $\alpha = 2\mu/m$ is low enough. In such a case, because of a low mutation rate or a high immigration rate, the half-isolated groups remain in the stable equilibrium solution in Figure 4; in other words, they are subspecies or races that can interbreed with the parental group. Each subspecies adapts to their living environment through natural selection. That is exactly what Darwin observed and described in his famous book (Darwin 1859). Second, the nonlinear nature of the new disaster-forced speciation model well fits the concept of “punctuated equilibrium” proposed by Eldredge and Gould (1972). The existence of a stable solution in a low-α case gives the theoretical basis to the stability of species which was postulated in the “punctuated equilibrium”. When $\alpha = 2\mu/m$ becomes high enough by some reason, the rapid speciation is initiated, leading to a macro-evolution. Forth, it includes all of the aro-, para-, and sympatric speciation depending on the value of $\alpha = 2\mu/m$. In particular, according to the new model, the sympatric speciation is possible without geological isolation, when the mutation rate μ is as high as unity per individual per generation. Such a sympatric speciation was suggested in small volcanic lakes in Cameroon (Lake Barombi Mbo and Lake Berman, Table 2). Finally, the disaster-forced biological evolution model explains why the speciation rate is considerably high around the mass extinction events (Raup and Sepkoski 1982; Sepkoski 1998; Bambach 2006), since they are likely to be due to the global disasters by encounters with nebulae (supernova remnants and dark nebulae; Kataoka et al. 2013a, b).

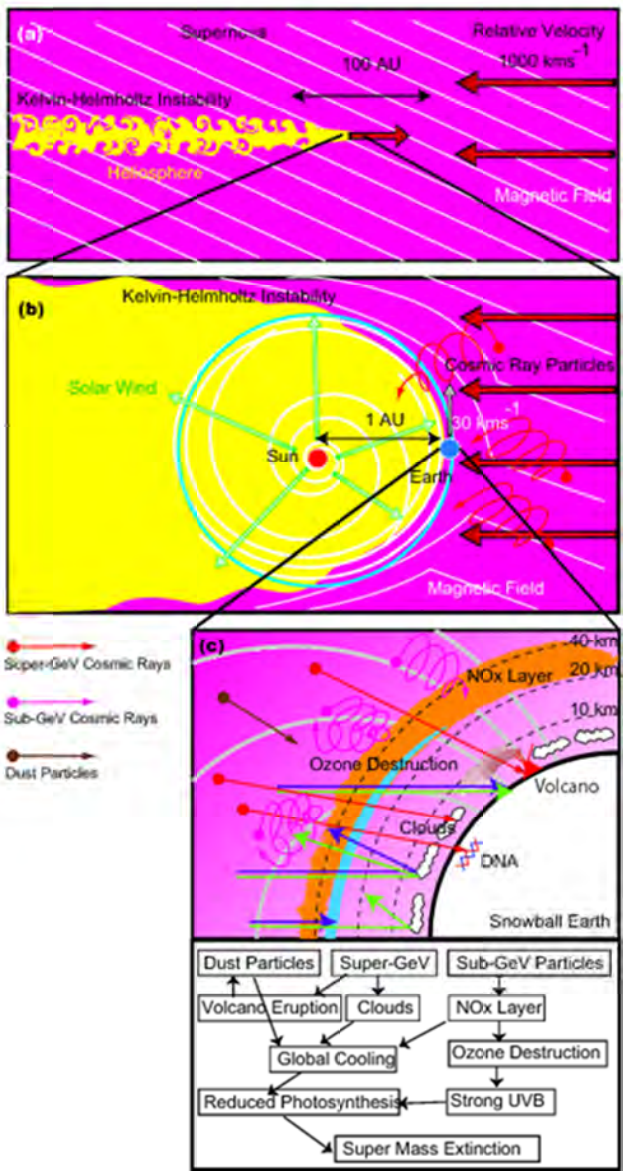

Figure 5. Schematic pictures of the heliosphere (yellow) during an encounter with a supernova remnant (pink). (b) The heliosphere shrinks to the Earth's orbit (breakdown of the first shield), where the gas pressure of the supernova remnant balances the solar wind pressure. (c) The cosmic ray flux increases by a large factor through the production of NOX in the stratosphere, which ultimately destroys the ozone layer (destruction of the third shield); the UV-B radiation can then penetrate the Earth's surface. Super-GeV cosmic rays enhance cloud formation. These three factors result in reduced significant reduction of photosynthesis, which leads to food and oxygen starvation in the biosphere, in other words, a disaster at global scale (taken from Kataoka et al, 2013).

The disaster-forced biological evolution model is, of course, a working hypothesis to be proven by evidences through the systematic investigation in the speciation hot spot in the present Earth, in other words, specifically the African Rift valley. The evidences can be obtained through the following future works:

1) Extensive surveillance of water, soils, and sediments in mineral contents including radioactive elements and natural radiation level of Olduvai Gorge and Lake Victoria in the African Rift Valley
2) Scientific drillings of sediments in fossil sites and lakes to reconstruct the paleo-environment including the history of volcanic activities and the climate variation. For example, the 2005 Malawi Scientific Drilling Project has been performed and succeeded to reconstruct paleo-environment in the period of 0.145-0.06 Ma (Scholz, C.A. et al. 2011). More comprehensive studies of other lakes are important to reconstruct paleo-enviroment.
3) Whole genome analysis of the variation of all kinds of organisms including animals, plant, and microorganism in African Rift Valley to study variation of genome within to evaluate the frequency of segmental duplication and activity level of transposons. The similar comparative studies in the regions with high radiation level caused by nuclear plant accidents (Chernobyl or Fukushima) are also important.
4) Sampling paleo-deep-marine sediments, such as found in Pacific-type accretionary complexes back to 4.0 Ga (Maruyama et al. 2011)

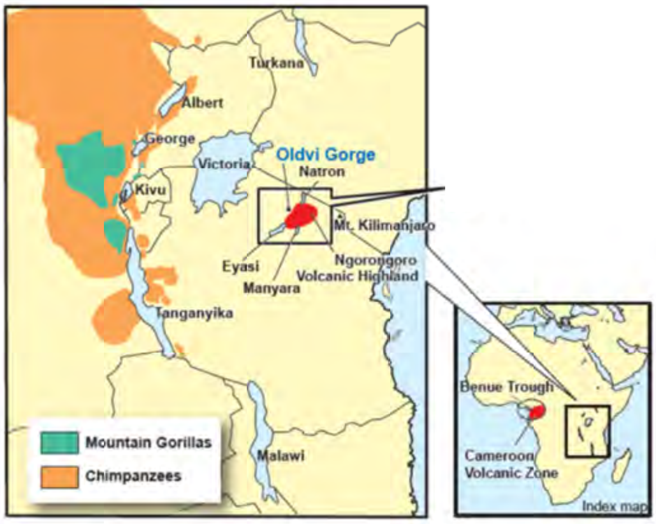

Figure 6. Map showing the African Rift Valley, Lake Victoria, “the Dawin’s Garden, Serengeti National Park, and the Olduvai Gorge. The birthplace of human beings is located among the east and west branches of the rift zone. Two closest relative species, Chimpanzees and Gorillas, live in the Rift zone (Figure 7).

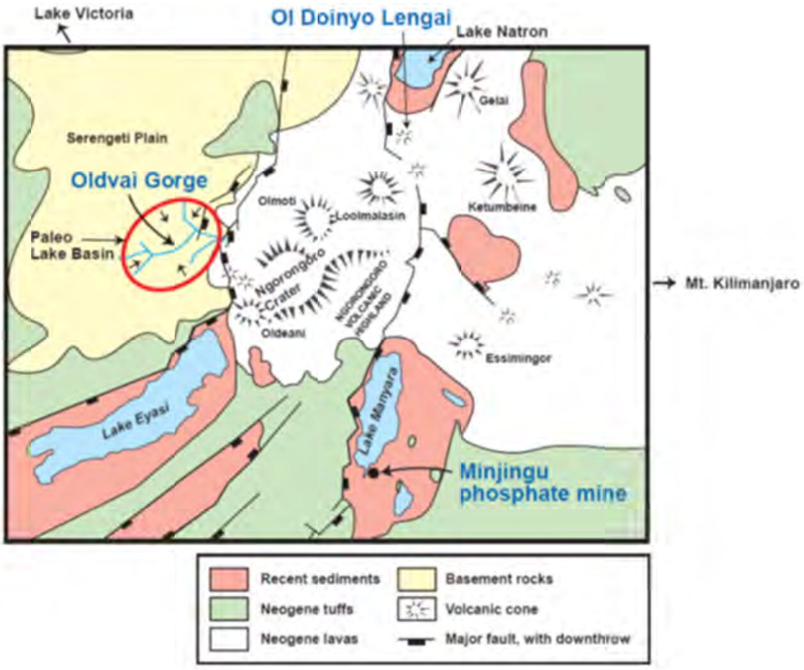

Figure 7. Oldvai Gorge and Ngorongro Volcanic Highland. The water in which flows into the gorge comes from the highland of carbonatite volcanoes.

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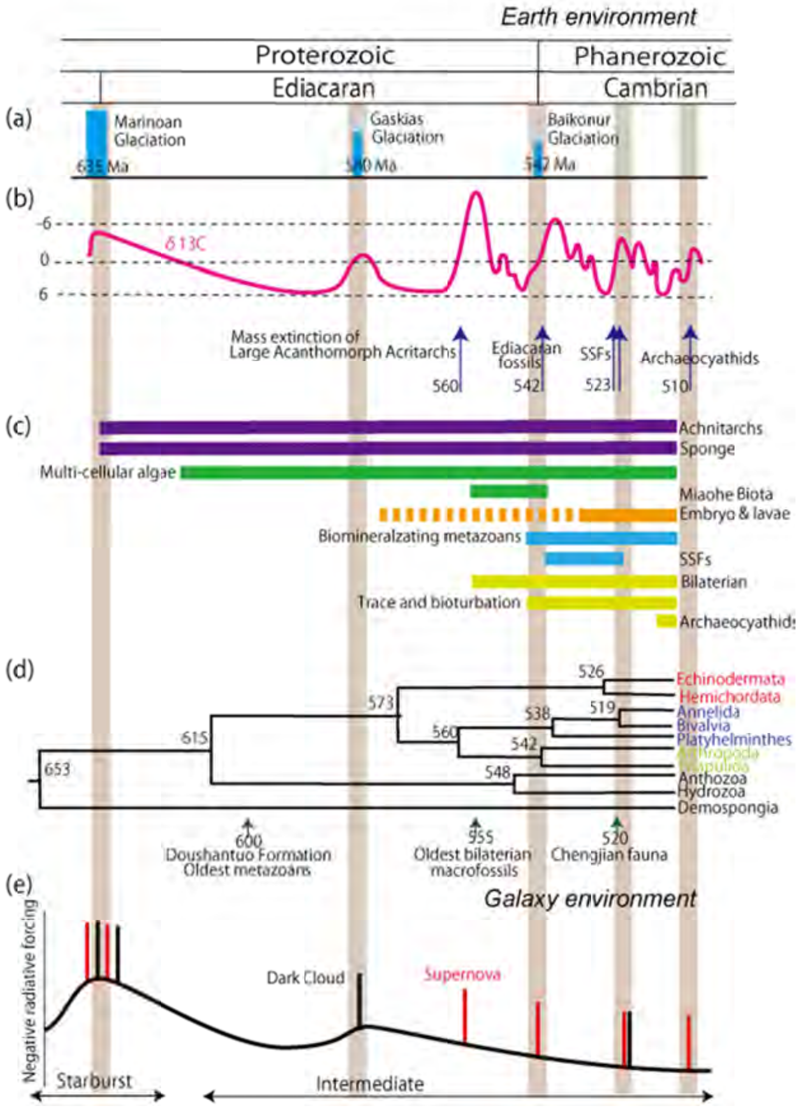

Figure 8 When the last snowball Earth glaciation (Marinoan glaciation) finished, the Ediacaran Period began. (a) Since then, there were two local glaciations, Gaskier (582 Ma) and Baikonur (542 Ma), and presumably numerous glaciations, but smaller in scale, were likely to have taken place in the Cambrian Period, as seen in local parallel unconformity (see a summary by Maruyama et al., in press). (b) Some glaciations are synchronized with the strong excursions in δ13C carbonate deposited on the continental shelf in the S. China craton (adapted from Zhu et al. (2007)), which correspond to the mass extinction events, such as those of large Acanthomorph Acritarchs (560 Ma), of Ediacaran fossils (542 Ma), of SSFs (523 Ma), and of Archaeocyathids (514 Ma), as indicated by the blue arrows (c). (d) A phylogenetic tree among the animal phyla is given by Peterson et al. (2004). The divergence times are estimated by the genomic distances among the species. Note that they generally include considerable error (more than 10%).

(e) Putative negative radiative forcing; the Milky Way Galaxy was gradually returning back to the normal state after the starburst around 0.6 Ga through the intermediate state, where supernova remnants dominate in the galactic disk. The encounters with the supernova remnants may drive environmental disaster leading to mass extinctions (as seen in section 3). The enhanced radiation triggers genome instability in the biological organisms at the surface of the Earth, accelerating their evolution (After Kataoka et al. 2013b).

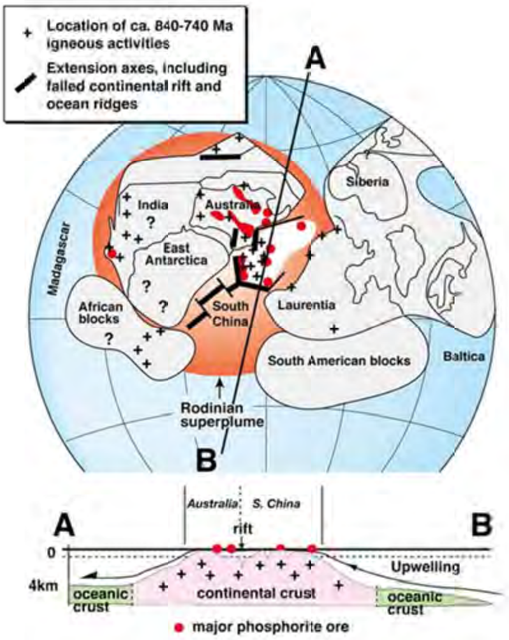

Figure 9 The **Three Gorge Area, South China, was in a rifting zone between Australia/East Antarctica and Laurentia/South American blocks in the Ediacaran/Cambrian and an evolutional hotspot which harbored the Cambrian explosion. Fossils are discovered in phosphate rocks widely distributed in the South China and Australia cratons.**