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The Nebula Winter: The united view of the snowball Earth, mass extinctions, and explosive evolution in the late Neoproterozoic and Cambrian periods

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ABSTRACT

Encounters with nebulae, such as supernova remnants and dark clouds in the galaxy, can lead to an environmental catastrophe on the Earth through the negative climate forcings and destruction of the ozone layer by enhanced fluxes of cosmic rays and cosmic dust particles. A resultant reduction in primary productivity leads to mass extinctions through depletion of oxygen and food starvations as well as anoxia in the ocean. The model shows three levels of hierarchical time variations caused by supernova encounters (1–10 kyrs), dark cloud encounters (0.1–10 Myrs), and starbursts (~100 Myrs), respectively. This "Nebula Winter" model can explain the catastrophic phenomena such as snowball Earth events, repeated mass extinctions, and Cambrian explosion of biodiversities which took place in the late Proterozoic era through the Cambrian period. The Late Neoproterozoic snowball Earth event covers a time range of ca. 200 Myrs long spanning from 770 Ma to the end of Cambrian period (488 Ma) with two snowball states called Sturtian and Marinoan events. Mass extinctions occurred at least eight times in this period, synchronized with large fluctuations in δ^{13}C of carbonates in the sediment. Each event is likely to correspond to each nebula encounter. In other words, the late Neoproterozoic snowball Earth and Cambrian explosion are possibly driven by a starburst, which took place around 0.6 Ga in the Milky Way Galaxy. The evidences for a Nebula Winter can be obtained from geological records in sediment in the deep oceans at those times.

1. Introduction

Multi-disciplinary geological investigations in the last decades produced three important concepts of natural history of the Earth. They are snowball Earth, mass extinctions, and Cambrian explosion, all of which remain enigmatic until now. These three phenomena, which appear independent at first sight, are closely related to one another. In fact, a number of normal glacial periods and mass extinctions occurred from the end of the last Snowball Earth event (Marinoan glaciation) through Ediacaran to the Cambrian periods, as summarized by Kopp et al. (2005), Zhu et al. (2007), and Maruyama et al. (2014).

First, a number of geological evidences support that the snowball-Earth events occurred at 2.2–2.4 Ga and 0.55–0.77 Ga in the Proterozoic eon (Hoffman and Schrag, 2002; Kopp et al., 2005; Maruyama and Santosh, 2008). Glacial deposits left by the retreating ice are found in many places (Hambrey and Harland, 1981). Paleomagnetic and geological data from these deposits suggest that they were emplaced at tropical low latitudes (Evans et al., 2000). In most locations, the glacial deposits are overlain by "cap" carbonate sediments (Grotzinger and Knoll, 1995). The snowball Earth hypothesis (Kirschvink, 1992; Hoffman et al., 1998) provides a single explanation for the following observations as follows. When the emplacement of glacial deposits reached a critical latitude (30° North and South), a runaway ice–albedo feedback (Budyko, 1968; Erikson, 1968; Sellers, 1969) took place, locking the Earth into a totally-frozen state, i.e. snowball, because of the high planetary albedo. In order to explain deglaciation, extremely high levels of atmospheric CO_2 released through volcanic emissions have been suggested (Caldeira and Kasting, 1992). The cap carbonates were formed during the ultragreenhouse climate in the aftermath of the glaciation (Hoffman et al., 1998). In fact, observations revealed

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that a snowball-Earth event of about a few hundred Myrs is not a simple contiguous super-cool period but rather is composed of several sets of super-cool periods followed by a super-warm period (Hoffman and Schrag, 2002), though the details of the snowball Earth, such as the synchronicity or ice- or slush-covered ocean, have been discussed (e.g., Maruyama and Santosh, 2008; Sansjofre et al., 2011).

An unresolved question associated with the snowball-Earth hypothesis is what caused the Earth to trigger the ice–albedo instability. However, the initiation of snowball-Earth events is difficult to determine based on previous models, which have only included internal forcings (e.g., the reduction of greenhouse gas in the atmosphere). A large negative radiative forcing equivalent to a 10% decrease in the solar constant, such as the reduction of $p(CO_2)$ to 0.01 mbar, was required to achieve a global-freezing solution. Maruyama and Liou (2005) argued that a suppression of volcanic activity might cause a significantly reduced $p(CO_2)$, driving the ice–albedo instability. Rino et al. (2008), however, found that volcanism was most active in the Proterozoic period, and thus, the atmosphere was most likely rich (by no means poor) in CO_2. Furthermore, Shaviv and Veizer (2003) found that there is no correlation between $p(CO_2)$ and ice-house and green-house climates in the last 600 Myrs, suggesting external forcings as the cause of changes in the climate of the Earth.

Second, by applying statistical methods to compiled fossil data, Raup and Sepkoski (1982) found “big five” mass extinction events, in which most of the species were exterminated in the Phanerozoic era. Mass extinction has played one of the critical roles in the entire history of the evolution of life. However, its cause has long been debated as either geological catastrophic events such as global-scale volcanism recorded at the P/T boundary (e.g., Isozaki et al., 2007) or astronomical events, such as asteroid impacts at the K/T boundary (Alvarez et al., 1980; Keller et al., 2004; Renne et al., 2013). In addition to volcanic- and impact-based hypotheses, there have been others including the breakup of a supercontinent and oxygen depletion (Stanley, 1987; Erwin, 1993; Hallam and Wignall, 1997; Erwin, 2006; Young, 2013a,b). Since the statistical analysis of mass extinctions through fossil records by Sepkoski (1981), several different models have been proposed, such as periodical impacts of icy meteorites whose orbits are perturbed by unknown planet X or an assumed binary star called Nemesis, both hypothesized to be of our solar system (Davis et al., 1984; Whitmire and Jackson, 1984; Whitmire and Matese, 1985). Aside from these ad-hoc researches on specific topics, a more comprehensive and integrated approach has awaited understanding of the influence of the galactic environment on the environment of the Earth, taking into account the new results based from investigations of the Milky Way Galaxy, which have greatly

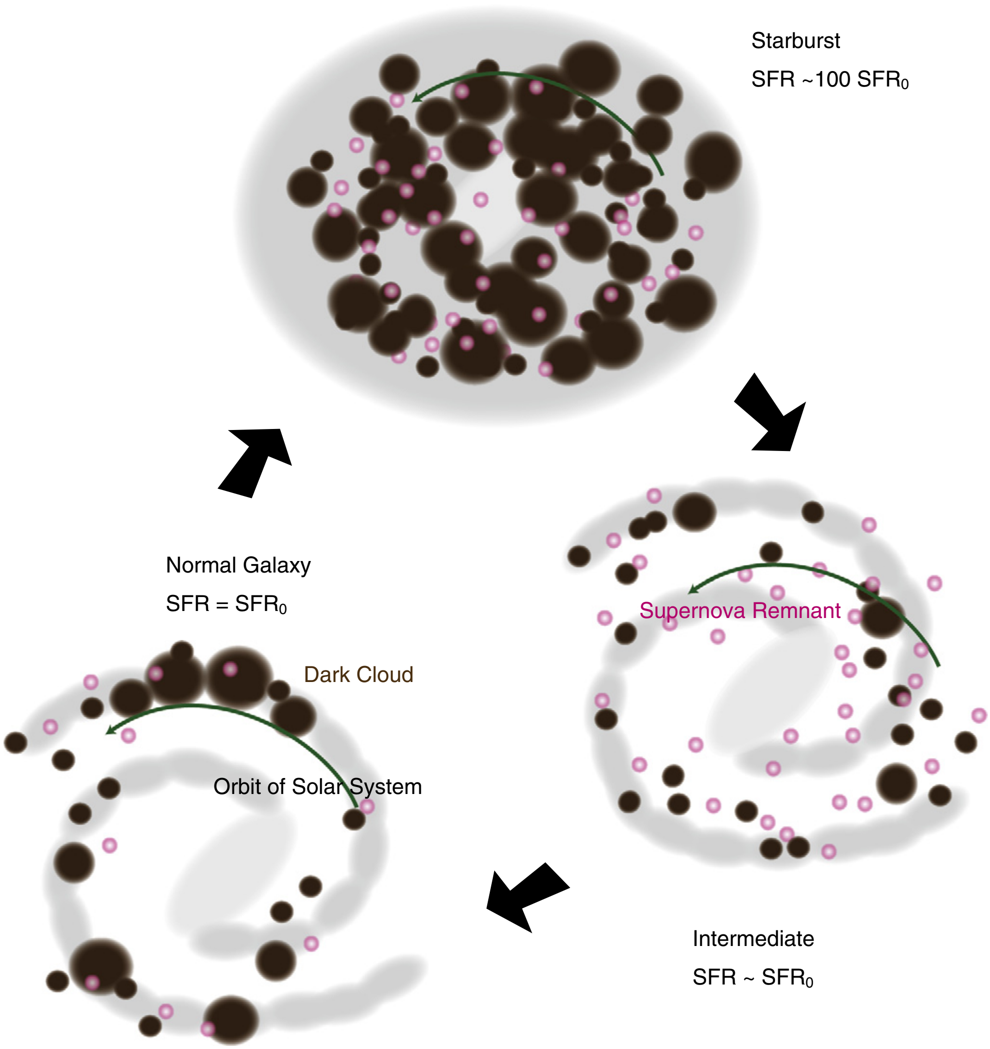

Fig. 1. Schematic illustration of the Milky Way Galaxy. Interaction with other galaxies or the accretion of a satellite galaxy triggers a starburst (top), in which the galactic disk is almost totally occupied by many dark clouds (large and small dark brown circles) with supernova remnants (small red circles) embedded therein. Star formation rate (SFR) is enhanced by a factor of ~100 compared with the normal state (bottom left). It returns back to the normal state through the intermediate state (middle right) where almost all dark clouds are evaporated by the heating of supernova explosions.