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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 $\delta^{13}C$ 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. (in press).

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

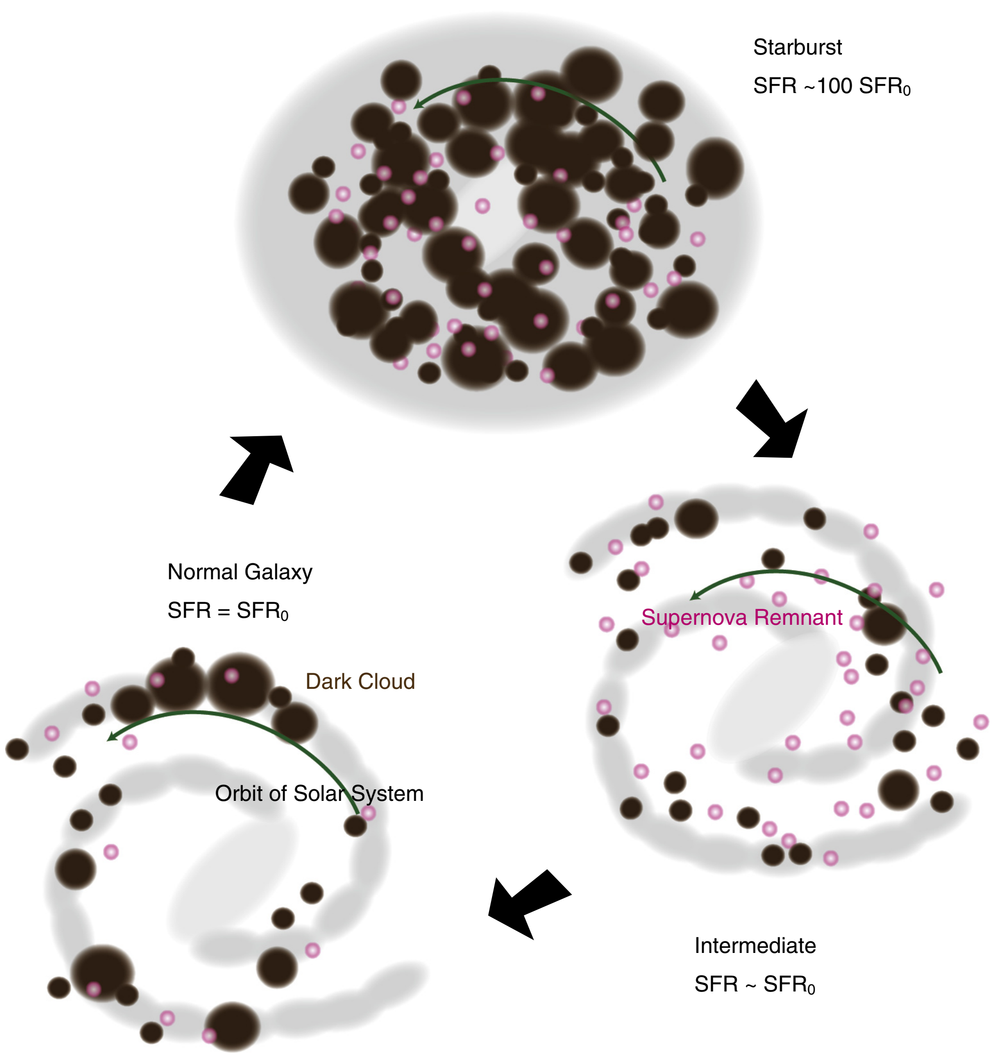

Fig. 1. Schematic illustration of the Milky Way Galaxy. Interaction with other galaxies or the accretion of a satellite galaxy triggers a starburst (top), in which the galactic disk is almost totally occupied by many dark clouds (large and small dark brown circles) with supernova remnants (small red 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. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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advanced in the last decades. For example, Isozaki (2009) has discussed the effect of galactic cosmic rays on the P–T boundary in terms of paleomagnetism.

Third, the importance of Ediacaran/Cambrian period was first pointed out by Gould (1989), who argued that all the extant animal phyla or the crown group of metazoan appeared in this relatively short time interval (70 Myrs, referred to as Cambrian explosion), while no new phyla have appeared since then (for more than 500 Myrs). As far as we know, there are no persuasive explanations why this period is so special. For example, Hoffman et al. (1998) proposed that the recovery from the snowball Earth events provided new niches and drove the explosive increase of biodiversity in the Cambrian period. However, the interval between the last Snowball earth events (Marinoan during 660–635 Ma) and the Cambrian explosion around 540–520 Ma is as long as 115 Myrs, which is too long to explain the Cambrian explosion by the snowball Earth event, comparing with the typical timescale of the evolution of biological systems.

Our approach presented in this paper is not geological but theoretical on the basis of the recent advancements in astronomy. The purpose of this work is to present a unified picture to explain the three important issues listed above through the natural history of the Earth in a comprehensive way, considering new data available during the period of the last snowball-Earth events (Marinoan during 660–635 Ma) to the Cambrian period (542–488 Ma), coupled with advanced information of the galactic environment, the latter having a major influence on the former. This is a forward model or a working hypothesis to inspire researches in a new direction to understand the Earth's natural history. Our theoretical basis is the starburst model, in which Kataoka et al. (2012) (hereafter Paper I) first conducted quantitative and systematic discussions on the external climate forcings on the Earth due to the encounters with nebulae in the galactic disk. They found that extensive and frequent encounters with nebulae can explain many features of the snowball-Earth events (Figs. 1 and 2). First, the negative radiative forcings during nebula encounters are strong enough to trigger the ice–albedo instability, leading to a snowball Earth during nebula encounters as described above. Second, the starburst of the Milky Way Galaxy provides a plausible explanation for the temporal pattern of the occurrence of the snowball-Earth events, which have occurred only twice (during the Early Paleoproterozoic period around 2.3 Ga, and the late Neoproterozoic period, 0.8–0.6 Ga). Statistics of stars and star clusters imply that the Milky Way Galaxy has experienced at least two starburst events: Burst I — 2.0–2.4 Ga (Rocha-Pinto et al., 2000) and Burst II — 0.6–0.8 Ga (de la Fuente Marcos and de la Fuente Marcos, 2004), as shown in Fig. 2. Bursts I and II correspond to the snowball-Earth events in the early Paleoproterozoic era and the late Neoproterozoic era, respectively. Third, it explains the hierarchical nature of the time variation of snowball Earth events. In the late Neoproterozoic era, two snowball Earth events occurred (Sturtian and Marinoan), separated by 100 Myrs. Recent observations revealed that the snowball Earth event 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). Such a hierarchical temporal structure in geological records of snowball-Earth events may correspond to the hierarchical nature of phenomena related to the Nebula Winter, or in other words, the timescale of three levels of hierarchy, i.e. supernova encounters (1–10 kyrs), dark cloud encounters (0.1–10 Myrs), and starbursts of the entire galaxy (~100 Myrs), respectively (Table 1). After the super-cool period is triggered by a nebula encounter, the climate becomes super-warm because of the accumulation of CO_2 in the atmosphere.

In the present paper, we provide an extended analysis by proposing a new unified model, referred to here as “Nebula Winter” of the snowball Earth events during the Proterozoic era and mass extinctions in the Ediacaran to Cambrian periods, which was followed by the explosive evolution of multi-cell organisms. We name “Nebula Winter” after the monumental paper of “Nuclear Winter” by Turco et al. (1983), since many of the processes reported here come from that paper. In Section 2, descriptions of the nebula encounters are shown. In Section 3, the model is compared with the recent data in Ediacaran through Cambrian periods. In Section 4, we compare the other models and discuss how to obtain evidence of a Nebula Winter.

2. Nebula Winter model

2.1. Nebulae in the Milky Way Galaxy

The Milky Way Galaxy has a galactic disk with a radius of 10 kpc and a thickness of 200 pc. Our solar system is located at approximately 8.5 kpc from the center of the Galaxy, inside the galactic disk. Many nebulae, such as dark clouds and supernova remnants, are distributed in the galactic disk. A dark cloud consists of high-density (100–1000 H cm^{-3}) and low-temperature (10–100 K) neutral gas. Cosmic dust also exists in a dark cloud, accounting for approximately 1% of the mass of the dark cloud. The size of the dark cloud ranges from 1 pc to 100 pc. In contrast, a supernova remnant is a shell structure produced by a shock wave caused by a catastrophic explosion of a star heavier than eight solar masses. Galactic cosmic rays with energies greater than ten GeV per nucleon (the super-GeV component) are accelerated in supernova remnants.

The Earth has a history extending back to 4.6 Gyrs, recording at least a few nebulae encounters. For the present Milky Way Galaxy, it has been estimated that a supernova occurs within 10 pc of the solar system approximately once per several hundred Myrs (Clark et al., 1977), whereas an encounter with a dense dark cloud of 2000/cc likely occurs once every billion years (Talbot and Newman, 1977). Furthermore, the Milky Way Galaxy is believed to have undergone several starbursts in the past. Rocha-Pinto et al. (2000) and de la Fuente Marcos and de la Fuente Marcos (2004) reconstructed the star-formation rate in the past Milky Way Galaxy based on the ages of stars and star clusters, finding that the Milky Way Galaxy has experienced at least two starburst

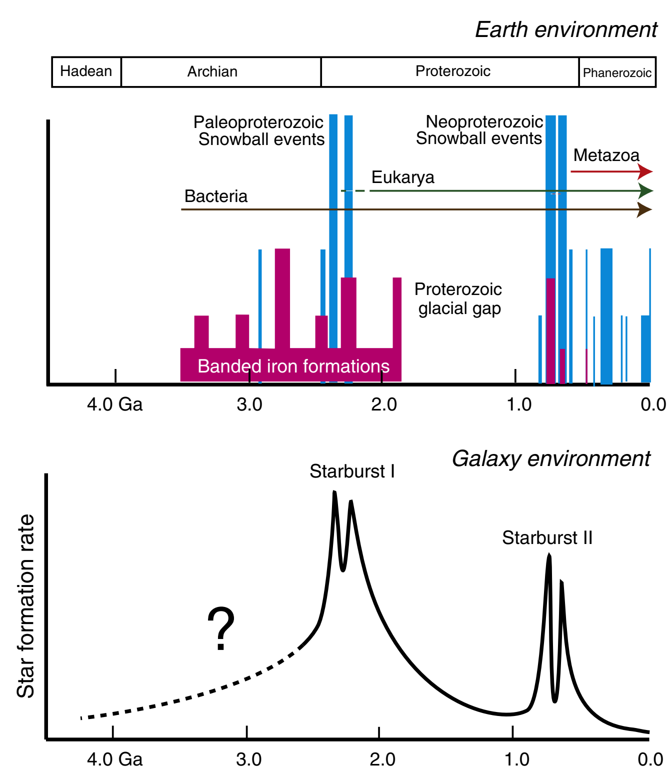

Fig. 2. (Top) Two snowball Earth events with other glaciations. (Bottom) Putative star formation rate in the Milky Way Galaxy is possibly enhanced by a large factor in two starburst periods: Starburst I (~2.2 Ga) and Starburst II (~0.6 Ga). The starburst periods coincide with the two snowball Earth periods. See Paper I for details.

Table 1
Time scale of supernova encounter, dark cloud encounter, and starburst of the Galaxy.

	Supernova encounter	Dark cloud encounter	Starburst
Time scale	1–10 kyrs	0.1–10 Myrs	~100 Myrs

events. A starburst is a phenomenon in which the star-formation rate in a galaxy is enhanced by dynamic interactions with nearby galaxies. A starburst galaxy (e.g., M82) is completely covered by thick dark clouds in which numerous supernova remnants are embedded. In such starburst periods, therefore, the frequency of nebula encounters is likely to be as high as one event in every several ten Myrs, and thus a plausible explanation for the snowball-Earth events.

A number of previous studies have suggested that an encounter with a nebula may lead to an environmental catastrophe (Whitten et al., 1963; Ruderman, 1974; Begelman and Rees, 1976; Clark et al., 1977; Talbot and Newman, 1977). An encounter of the solar system with a nebula, such as a dark cloud or a supernova remnant, enhances the flux of cosmic dust particles and cosmic rays, which leads to global cooling and destruction of the ozone layer. The cosmic dust particles remain in the stratosphere for more than several years, working as sunscreens. Sub-GeV cosmic rays, which penetrate into the stratosphere, produce NO_X that destroys the ozone layer. Largely enhanced NO_2 can also reduce the amount of radiation received at the ground (Reid et al., 1978). In contrast, super-GeV cosmic rays produce charged ions in the troposphere that enhance aerosol nucleation (Svensmark et al., 2007; Kirkby et al., 2011), leading to greater cloud cover and increased Earth albedo (Svensmark and Friis-Christensen, 1997; Svensmark, 2007).

Fig. 3 illustrates the Nebula-Winter model, based on Paper I. "Three shields" of the heliosphere, geomagnetic field, and ozone layer protect the Earth's environment against "three spears" of cosmic dust particles, sub- and super-GeV cosmic rays, and UV-B radiation from the Sun. An encounter with a supernova remnant or a dark cloud causes a significant enhancement in the "three spears" and breakdown of the "three shields", leading to catastrophic events such as snowball-Earth events and associated mass extinctions. In the following subsection, we will describe what happens in the dark-cloud encounter and supernova encounter, respectively.

2.2. Dark-cloud encounter

Fig. 3C and D depicts the Earth's environment during a dark-cloud encounter when the heliospheric boundary shrinks by a factor of 100 and locates around the orbit of the Earth (breakdown of the first shield). The heliospheric boundary becomes unstable against the Rayleigh–Taylor instability, forming many cloudlets. These cloudlets orbit the Sun independently, gradually sinking down to the Sun. The shocks between these dense cloudlets and the solar wind constantly accelerate the sub-GeV component of cosmic rays in the heliosphere, unlike the present solar system, where such acceleration occurs only after intensive solar-flare events. The super-GeV cosmic rays also freely penetrate into the Earth's orbit. The super-GeV cosmic rays enhance the radiation dose at the ground, possibly causing global cooling via enhancing the cloud formation. The sub-GeV cosmic rays penetrate the stratosphere of the polar region of the Earth and destroy the ozone layer through NO_X formation (breakdown of the

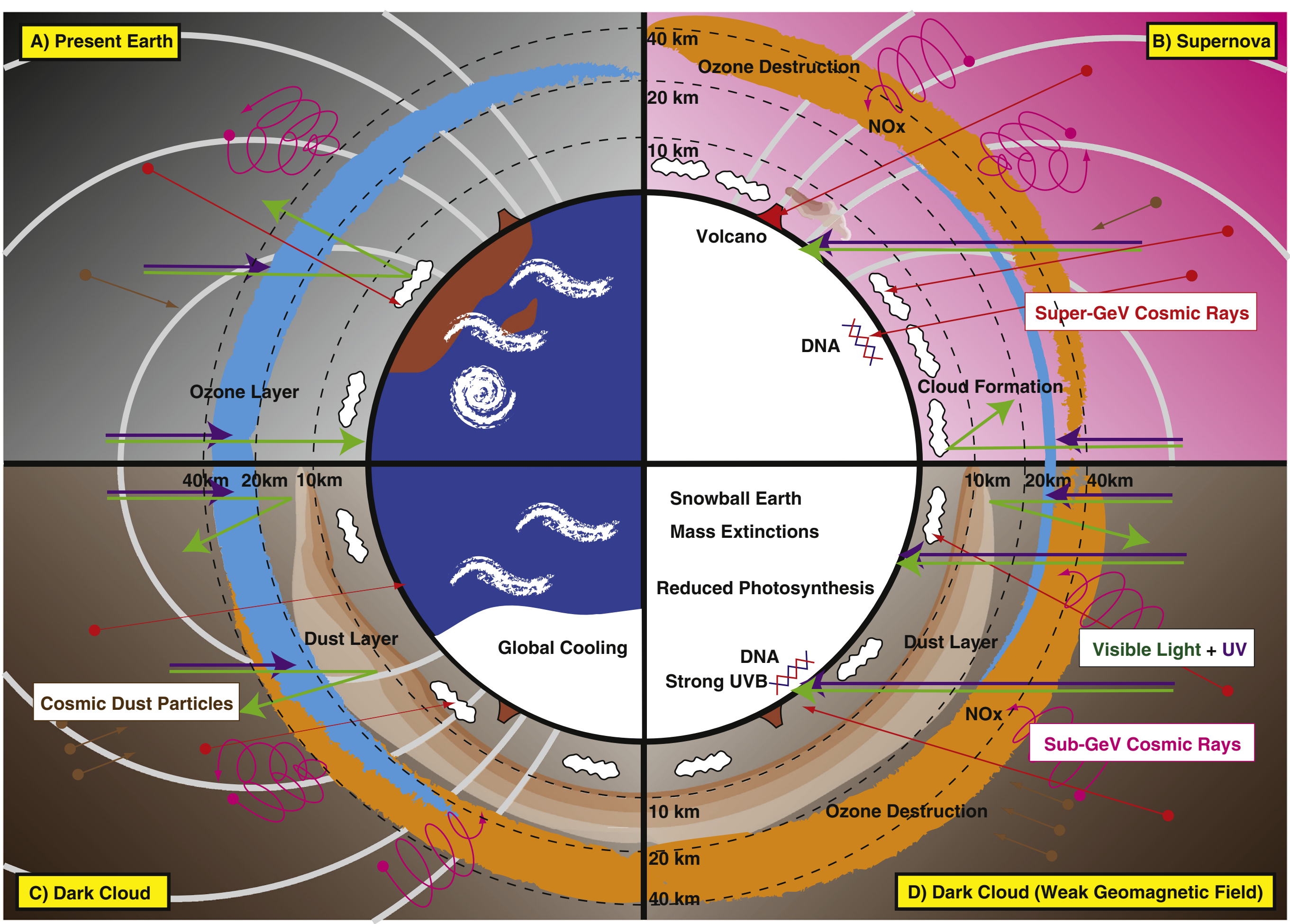

Fig. 3. Illustration of the Nebula Winter model. The large enhancement of "three spears" of cosmic rays, cosmic dust particles, and UV radiation from those at (A) the present Earth can induce catastrophic events of the Earth encountering with (B) nearby supernova remnant and (C) dark cloud, especially during (D) weak geomagnetic field.

third shield), particularly during geomagnetic excursions or reversals (breakdown of the second shield, Fig. 3D). The largely enhanced NO_2 may also contribute to the global cooling. Furthermore, a large amount of cosmic dust particles in the dark cloud accretes on the Earth and causes global cooling.

Fig. 4 shows the time profiles of factors influencing the Earth's environment during an encounter with a dark cloud with a central density of 2500 H cm^{-3}, a Gaussian density profile with a scale of 10 pc across, and a relative velocity of 20 km s^{-1}. Fig. 4b shows the radiative forcings due to cosmic dust, cosmic rays, and NO_2. The most important effect is the effect of cosmic dust. Pavlov et al. (2005) found that cosmic dust particles with submicron size persist in the stratosphere for several years and that the radiative forcing of cosmic dust is as strong as −15 W m^{-2} when the solar system passes the densest part of the dark cloud, which well exceeds the snowball forcing of −14 W m^{-2}.

Furthermore, as illustrated in Fig. 5, a dark cloud perturbs the orbits of comets/asteroids orbiting in outer space or specifically in the so-called Oort cloud of the solar system, which may cause multiple impact events on the Earth (Matese et al., 1995; Mazeeva, 2004; Jakubik and Neslusan, 2008). Assuming the radius of the Oort cloud (10^4 AU) and the radius of dark cloud (8 pc), velocity perturbation by the dark cloud is as high as:

$$dv = \left(\frac{2GM_{DC}}{r}\right)\left(\frac{a}{r}\right)\left(\frac{1}{v_{DC}}\right)$$
$$= 29\ \mathrm{ms}^{-1}\left(\frac{M_{DC}}{10^{35}\ \mathrm{kg}}\right)\left(\frac{a}{10^4\ \mathrm{AU}}\right)\left(\frac{r}{8\ \mathrm{pc}}\right)^{-2}\left(\frac{v_{DC}}{12\ \mathrm{km\ s^{-1}}}\right)^{-1}.$$

Since Kepler velocity is about 290 ms^{-1} in the Oort cloud, the change in the velocity of comet/asteroids can be as large as 10% during a dark-cloud encounter. The loss-cone around the Earth's orbit is refilled by the perturbed comets and asteroids in the Oort cloud. The frequency of the comet/asteroid impacts increases considerably during the dark cloud encounter (Mazeeva, 2004).

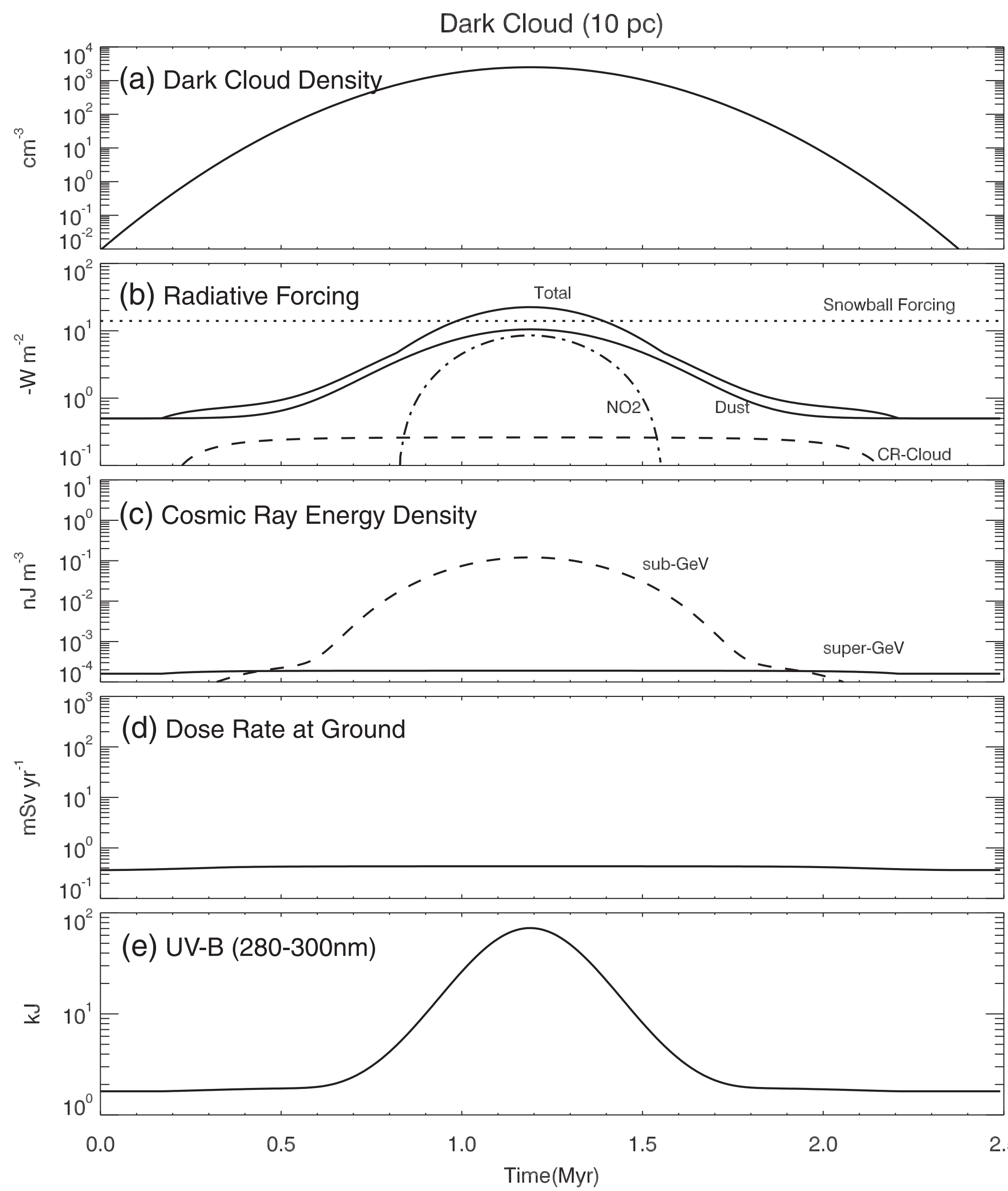

Fig. 4. Time profile of an encounter with a dark cloud with a diameter of 10 pc and a central density of 2500 H cm^{-3}; (a) interstellar gas density; (b) negative radiative forcings (solid curve: total; dashed curve: cloud albedo by cosmic rays; dash–dot curve: NO_2 effect; dash–dot–dot curve: cosmic dust effect; and dotted line: snowball forcing of −14 W m^{-2}); (c) cosmic ray energy densities outside of the Earth's magnetosphere; (d) radiation dose rate at the ground; and (e) UV-B intensity under a weak geomagnetic field (after Paper I).

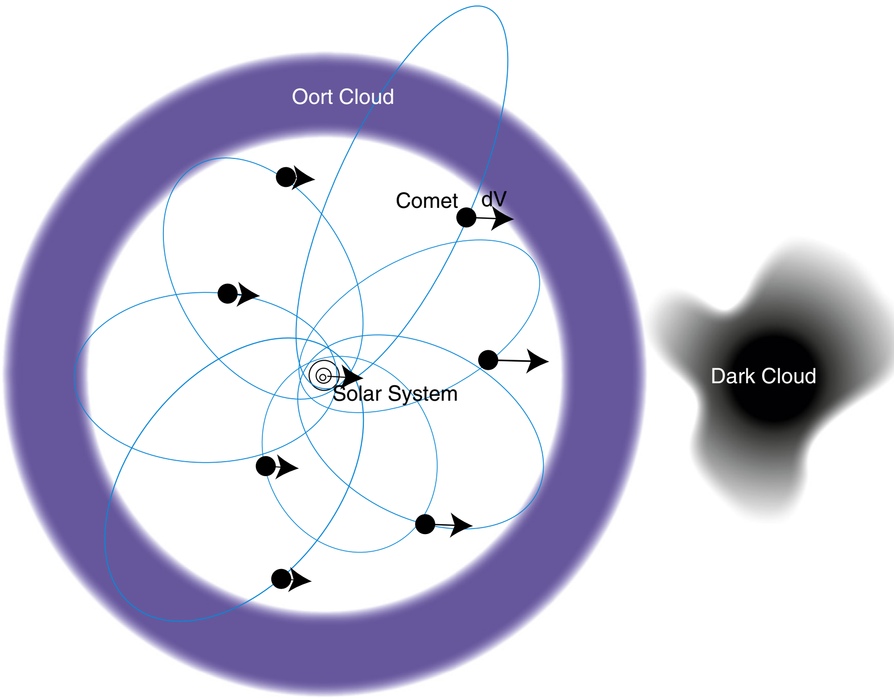

Fig. 5. A dark cloud encounter perturbs the orbits of comets/asteroids in the Oort cloud.

The flux of the sub-GeV cosmic rays increases by a factor of approximately 1000 (Fig. 4). This increase in flux leads to the destruction of the ozone layer in the stratosphere via the production of NO_X (in particular, NO and NO_2). Ozone depletion has been observed in the polar region during large solar-proton events (Jackman et al., 2005). The destruction of the ozone layer is limited to the polar region when the geomagnetic field is as strong as that at present time (~10^{-5} T). The destruction, however, extends to lower latitudes during geomagnetic excursions when the geomagnetic field is weak (Fig. 4d). Because at least one geomagnetic excursion or reversal is expected during a 10-Myr period (Cox, 1975), the encounter with a dark cloud, which extends for several Myrs, is sufficiently long to encompass several geomagnetic excursions and reversals.

Fig. 4e shows the UV-B radiation increase due to the destruction of the ozone layer by enhanced sub-GeV cosmic rays, assuming an ozone column density of 300 Dobson Units and a geomagnetic field as low as 10% of the present value. The UV-B radiation destroys the photosynthesis mechanisms of phytoplankton, and the primary productivity decreases to 30–50% of the present level. In fact, in the present polar ocean exposed to the enhanced UV-B flux due to the ozone hole, a reduced primary productivity of phytoplankton (Smith and Baker, 1989) has been observed. Furthermore, the stratospheric NO_2 enhancement drives global cooling by up to 3 K (Reid et al., 1978). The reduced primary productivity together with the global cooling causes a reduced oxygen density both in the atmosphere and in the ocean (anoxia), negative excursions of the δ^{13}C, and mass extinction.

2.3. Supernova remnant encounter

Fig. 3B shows the Earth's environment during an encounter with a supernova remnant when the heliosphere shrinks to around the Earth's orbit (breakdown of the first shield). The cosmic rays of both the super- and sub-GeV components increase by a large factor (100–1000 times). The duration of the encounters is 10^3 to 10^4 yrs depending on the supernova distance and the surrounding gas density. The increased cosmic-ray flux also depletes the ozone layer through the production of NO_X, leading to an enhanced UV-B intensity (breakdown of the third shield).

We used the PHITS code (Niita et al., 2010) to calculate the atmospheric impact of cosmic rays from a nearby supernova remnant with the hardest (power of −2) spectra. Protons with energies from 100 MeV to 1 TeV were considered as the source particle inducing the air shower. Details of the calculation procedure are given in Sato et al. (2008). The relative amplitude of cosmic-ray flux v.s. present levels is assumed to be 1000 fold at 1 GeV, considering the nearby supernova at a 10 pc distance. As shown in Fig. 6, it is found that the absorbed dose rate in the air can be enhanced at most 10^4 times larger than the present level at the ground if the cosmic-ray spectrum is flat enough.

The influence of a supernova encounter with the environment of the Earth is summarized in Fig. 7. First, the maximum negative radiative

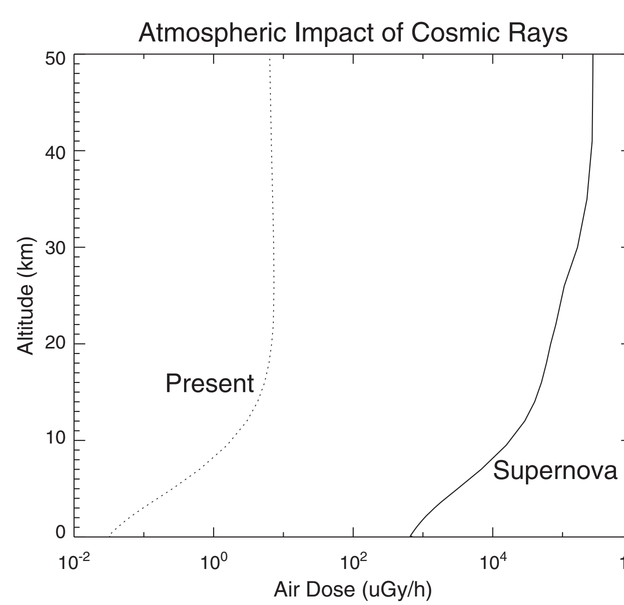

Fig. 6. Dose rate due to cosmic rays during supernova encounter with a spectral index of −2 (solid curve). The present profile of cosmic ray impact is shown by dotted curve as a reference.

forcing due to the increased flux of sub-GeV and super-GeV cosmic rays is approximately −20 W m^{-2} for several thousand years and well exceeds the snowball forcing of −14 W m^{-2}. Second, the dose rate at the ground reaches 1 Sv yr^{-1}, which has a significant effect on the biological systems via the genome instability. Third, the increased cosmic-ray flux depletes the ozone layer through the production of NO_X, leading to an enhanced UV-B intensity. The reduction of primary production due to this enhanced UV-B radiation, together with global cooling, causes a catastrophic perturbation of the ecosystem at the surface of the Earth during a supernova encounter, similar to the effect caused by the encounter with a dark cloud.

3. Late Neoproterozoic snowball Earth and Cambrian explosion

Snowball-Earth events have been documented in the Neoproterozoic based on glacial-deposit records at low-latitudes near equatorial regions (Hoffman and Schrag, 2002). In addition to the nearly complete snowball periods, Sturtian (710–685 Ma) and the Marinoan (660–635 Ma) (Fig. 7), local glacial periods have also been present, such as Kaigas (770–730 Ma), Gaskier (582 Ma), and Baikonur (542 Ma), but presumably more prevalent and smaller in scale in the Cambrian as seen by a local parallel unconformity (see a summary by Maruyama et al., in press).

Cloud (1948) first pointed out that the Cambrian explosion highlighted a sudden appearance of metazoans at the onset of the Cambrian, and the majority of the living metazoan phyla appeared in this period. It has been recently revealed that the Cambrian explosion was not a single event but a complex event, composed of three distinct major phases: (1) Ediacaran fauna, (2) small shelly fossils (SSFs), and (3) Chengjian faunas (mega-fossils such as first fish) by the end of Early Cambrian (Shu, 2008). Gould (1989) emphasized that it was an extremely unique event because there was no association to mass extinctions. On the contrary, detailed analysis has revealed that the period from 635 Ma to the end Cambrian was a time when the frequency of mass extinctions

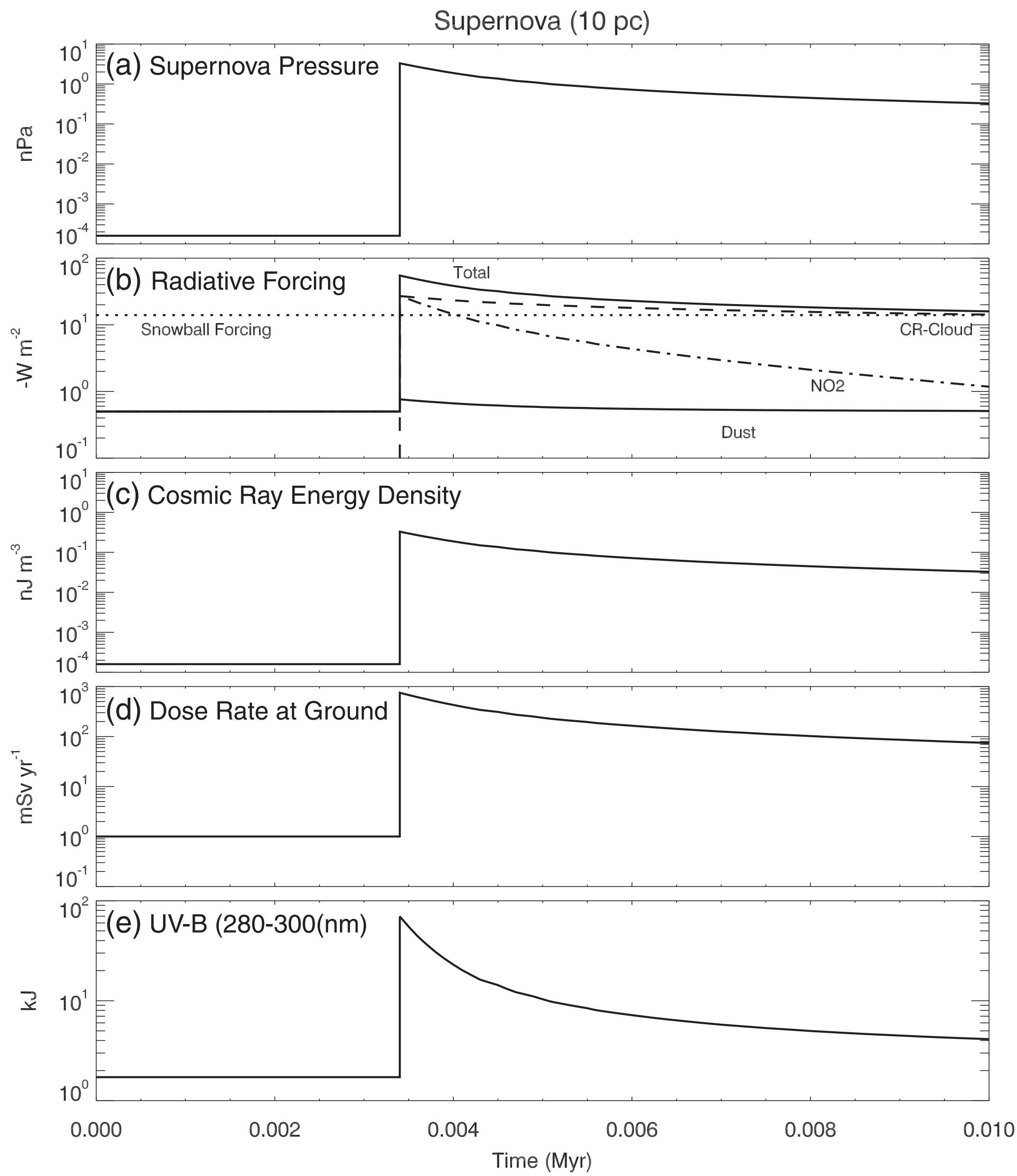

Fig. 7. Time profiles of the encounter with a supernova remnant that exploded at a distance of 10 pc and with an interstellar gas density of 0.5 H cm^{-3}; (a) pressure of the post-shocked gas of the supernova remnant; (b) negative radiative forcings (solid curve: total; dashed curve: cloud albedo by cosmic rays; dash–dot curve: NO_2 effect; dash–dot–dot curve: cosmic dust effect; and dotted line: snowball forcing of −14 W m^{-2}); (c) cosmic ray energy density; (d) radiation dose rate at the ground; and (e) UV-B intensity (after Paper I).

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was at least five times higher than in the Phanerozoic (Zhu et al., 2007). For example, based on the compilation of all existing paleontological descriptions of this period, Zhu et al. (2007) recognized the presence of frequent mass extinctions such as the mass extinctions of large Acanthomorph Acritarchs (560 Ma), Ediacaran fossils (542 Ma), SSFs (523 Ma), and Archaeocyathids (514 Ma). Moreover, based on the curve of carbonate deposited on the continental shelf in the late Neoproterozoic in the S. China craton, which is related to mass extinctions, they have further speculated that eight periods of mass extinctions were present in the time span from 635 Ma to 488 Ma (Zhu et al., 2007), observations of which are consistent with the recent chemostratigraphic studies of multiple drilled cores (Tahata et al., in press; Ishikawa et al., in press; Sawaki et al., this volume; Yamada et al., under review). Bambach (2006) also independently speculated the presence of more than four mass extinctions in the Cambrian, and those being larger than the big five events in post Ordovician mass extinctions (Fig. 8).

These numerous mass extinctions from Ediacaran through the Cambrian period are likely to be caused by the nebula encounters in the intermediate state after the starburst of the Milky Way Galaxy. In such an intermediate state, the solar system predominately encountered supernova remnants; though most of the dark clouds were evaporated, the supernova explosions still remain frequent enough. Glacial deposits due to the Nebula Winter of supernova remnants are difficult to be formed or found since they are as short as 1–10 kyrs, although they were long enough to drive mass extinctions.

This higher frequency of mass extinctions in this period may explain the rapid evolution in the Cambrian period. Natural radiation level is 100–1000 times higher even on the ground during the supernova encounter than that in the present time; it is high enough to trigger genome instability in biological organisms (Dubrova, 2006), which leads to a significant increase in the frequency of chromosomal rearrangement in offsprings (Aghajanyan et al., 2011). It possibly accelerates the evolution and adaptation of new species in the new environment through creations of new genes by segmental or whole-genome duplication (Ohno, 1970) and gene shuffling. In fact, as can be seen in Fig. 9, the new phyla of metazoan branched just after the mass extinction events. Furthermore, in the Ediacaran period, the lineage of vertebrate underwent two-round, whole-genome duplications, which gave them vast freedom to try different body plans and metabolisms. These whole genome-duplication events are likely to be related to the genome instability perturbed by the encounters with supernova remnants.

Moreover, the Acraman impact crater was formed ca. 580 Ma (Grey et al., 2003; Meert and Lieberman, 2008), which may be related to the Gaskias glaciation. The ultimate cause of the impact may be the gravitational perturbation exerted on asteroids/comets due to an encounter with a dark cloud (see Subsection 2.2). Such potential extra-terrestrial phenomena merit further detailed investigation.

4. Discussions

A Nebula-Winter model has been developed to present a unified picture in order to explain snowball-Earth events, mass extinctions, and Cambrian explosion in the Ediacaran through the Cambrian periods in terms of changes in the galactic environment by the starburst of the Milky Way Galaxy around 0.6 Ga and the gradual recovery to the normal state through the intermediate state (Fig. 1).

The extensive and frequent encounters with nebulae due to the starburst of the Milky Way Galaxy can explain many features of the snowball-Earth events (Paper I; Figs. 1 and 2). The previous snowball-Earth models, in which only internal forcings were considered, cannot explain the triggering mechanism nor occurrence pattern, while the Nebula Winter model, which includes external forcing from outside of the Earth, can explain both. First, the negative radiative forcing is strong enough to trigger ice–albedo instability, leading to a snowball Earth during the solar-system encounters as described above. Second, the Nebula-Winter model provides a plausible explanation for the temporal pattern of the occurrence of the snowball-Earth events that occurred only twice, during the early Paleoproterozoic era (around 2.3 Ga) and the late Neoproterozoic era (0.8–0.6 Ga: Fig. 2). The statistics of stars and star clusters imply that the Milky Way Galaxy has experienced at least two starburst events, i.e., Burst I — 2.0–2.4 Ga; (Rocha-Pinto et al., 2000) and Burst II — 0.6–0.8 Ga (de la Fuente Marcos and de la Fuente Marcos, 2004). Starbursts I and II correspond to the snowball Earth events in the early Paleoproterozoic era and the late Neoproterozoic era, respectively. Third, it also explains the hierarchical nature of the climate change in the Late Neoproterozoic era in general. Two snowball Earth events occurred (Sturtian and Marinoan), separated by 100 Myrs. Observations revealed that a snowball-Earth event 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). Such a hierarchical temporal structure in the geological records of snowball-Earth events may correspond to the hierarchical nature of phenomena related to the Nebula Winter; in other words, the timescale of three levels of hierarchy, i.e., supernova encounters (1–10 kyrs), dark cloud encounters (0.1–10 Myrs), and starbursts of the entire galaxy (~100 Myrs), respectively.

Following the starburst, the Milky Way Galaxy gradually returned to a more normal state, which we refer to as an intermediate state (Fig. 1), in which supernova remnants are predominant in the galactic disk, since most of the dark clouds were evaporated by the heating of supernova explosions. The frequent encounters with nebulae, particularly with supernova remnants, can lead to multiple mass-extinction events reported in the Ediacaran through Cambrian periods.

The nebula encounters are likely to induce rapid evolution and speciation which leads to the explosive emergence of new types of organism after mass extinctions. There are four necessary conditions for rapid

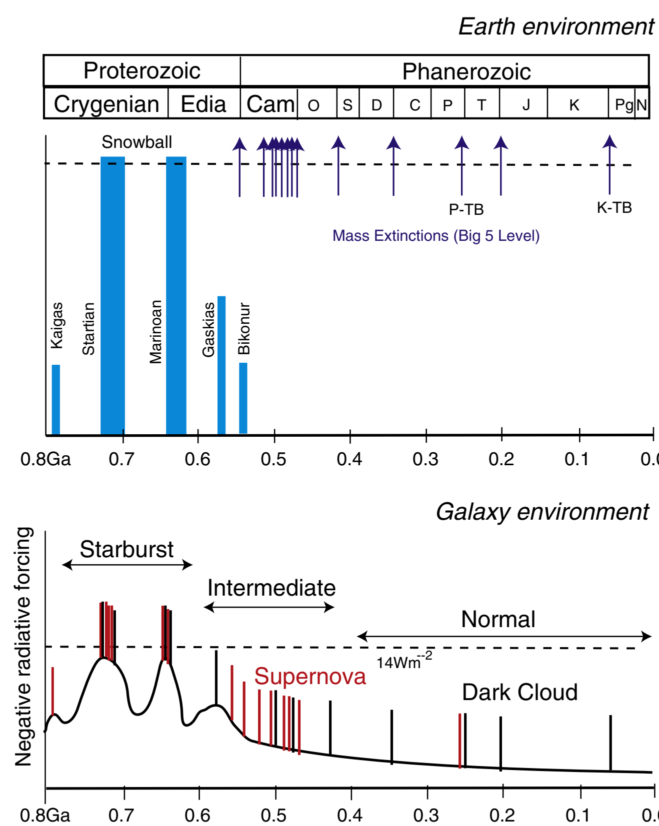

Fig. 8. (Top) The Sturtian (710–685 Ma) and Marinoan (660–635 Ma) were nearly complete snowball states, while Kaigas (770–730 Ma), Gaskier (582 Ma), and Baikonur (542 Ma) were local glacial periods. (Bottom) Putative external negative forcings from 0.8 Ga to the present. Milky Way Galaxy underwent starburst in 0.8–0.6 Ga and then gradually returned back to the normal state (0.4 Ga to present) through the intermediate state (0.8–0.4 Ga). See also Fig. 1.

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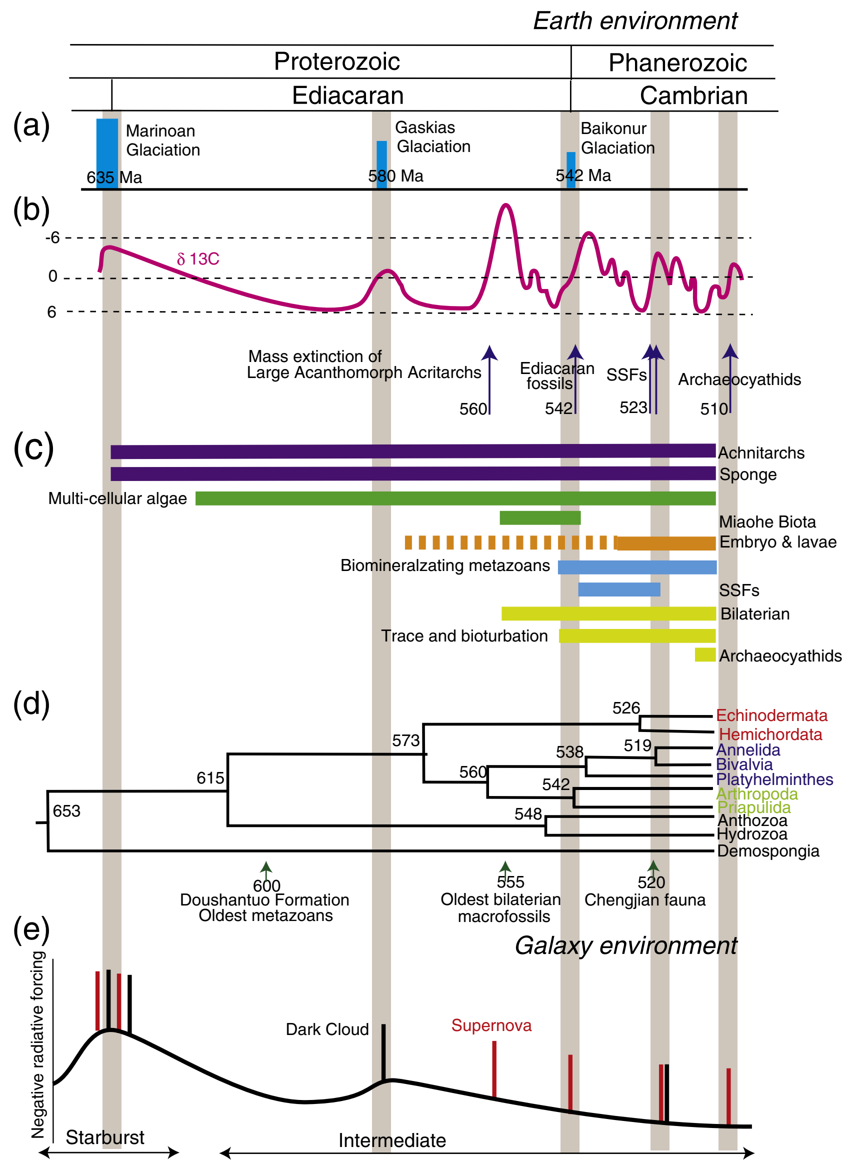

Fig. 9. When the last snowball Earth glaciation (Marinoan glaciation) finished, Ediacaran period started. (a) Since then, there were two local glaciations, Gaskier (582 Ma) and Baikonur (542 Ma) and presumably numerous glaciations but smaller in scale were likely to take place in Cambrian period as seen in local parallel unconformity (see a summary by Maruyama et al., in press). (b) Some of them are synchronized with the strong excursions in δ^{13}C 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 in 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; 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 catastrophe to lead mass extinctions. The enhanced radiation triggers genome instability in the biological organisms on the ground to accelerate their evolution.

speciation. These are as follows: a small population (Mayr, 1942, 1954; Ohno, 1970), strict isolation (Kimura and Weiss, 1964), high mutation rate, and availability of new niches. Mass extinction events of nebula encounters satisfy all of them. First, a population group is naturally expected to become small due to difficult environmental conditions during a nebula encounter. Secondly, the habitat drastically shrinks and the immigration among the groups becomes difficult during catastrophic events. The strict isolation of a small population group is naturally achieved during a nebula encounter. Third, the mutation rate becomes considerably higher because of the genome instability through the enhanced natural radiation level during a nebula encounter. Fourth, many new niches become available for new species when a nebula encounter is over. Ediacaran to Cambrian periods were, therefore, in an ideal situation for the rapid evolution of biological organizations, since all of the four conditions were satisfied.

Noteworthy, Sepkoski (1981) found that the global speciation rate on the Earth in the last 600 Myrs has two distinct peaks, followed by exponential decreases in the Cambrian period and the post P/T mass extinction event. We will discuss this matter in more detail in a separate paper.

The Nebula-Winter model is a working hypothesis. Evidence to support the model may be provided by detailed geochemical studies, including isotope studies of platinum-group elements or plutonium in deep-sea sediments where the accumulation speed is sufficiently low. These types of studies may corroborate the existence of a large amount of exosolar grains in the sediment during the snowball-Earth period. As possible evidence of a very recent supernova, an excess of ^{60}Fe has been observed in a Fe/Mn crust in marine sediments (Knie et al., 2004; Fields et al., 2005). This excess was interpreted to be a signature of a supernova explosion 2.8 ± 0.4 Myrs ago.

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Bodiselitsch et al. (2005) found iridium anomalies at the base of all cap carbonates both after the Marinoan and Sturtian glaciations; iridium and other platinum-group elements are typical proxies for extraterrestrial (including exosolar) materials and are much more abundant than in the Earth's upper mantle and crust. These authors interpreted the anomalies to be the product of the rapid accumulation of extraterrestrial material once trapped in the surface ice and later transported to the ocean floor via the melting of the ice at the end of the glaciation. Nevertheless, the excursion of iridium may also reflect the enhanced flux of extraterrestrial material due to an encounter with a nebula.

Moreover, ^{244}Pu is expected to remain in the Fe/Mn crusts of interest. Fields et al. (2005) estimated the ^{244}Pu production by a supernova explosion to approximately 0.9×10^{-7} solar masses. The expected flux of the ^{244}Pu at the Earth is approximately 10–16 kg m^{-2} yr^{-1}. A significant amount (0.1 Bq m^{-2}) of the accreted ^{244}Pu remains in the sedimentary rocks, even considering the half-life of ^{244}Pu (80 Myrs).

The existence of abundant 100-μm spherical iron balls in pelagic sediments is also possible direct evidence. For example, Miono et al. (1993) argued that the spherules accumulate in Paleozoic–Mesozoic bedded cherts. These spherules are generally believed to originate from micro-meteorites. The Nebula Winter model can be tested by similar but further advanced investigations, including the analysis of the abundance of the isotopes and platinum family elements of the minerals separated from spherules in the pelagic sediments, detailing their exosolar nature. In addition, mineralogical investigations on the ages, the abundances of platinum family elements, and the isotope ratios of the minerals of the exosolar grains in the pelagic sediments at that time, will clarify the influence of the galactic environment on the natural history of the Earth.

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