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Cosmic Rays, Clouds, and Climate

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Abstract

This paper discusses how cosmic rays may influence Earth's clouds, climate, and biosphere. Cosmic-ray ionisation promotes the formation and growth of aerosols into cloud condensation nuclei, potentially increasing cloud reflectivity and altering Earth's energy balance. Evidence for this mechanism comes from laboratory experiments, atmospheric observations, and modelling. The paper discusses correlations between cosmic-ray variability and climate change across timescales from days to millions of years, along with proposed links between supernova activity, temperature, oxygen production, and biodiversity. To clarify the relative climatic effects of cosmic rays and greenhouse gases and improve estimates of climate sensitivity to carbon dioxide, the plan is to incorporate this mechanism into global climate models.

Keywords: Cosmic rays; clouds; climate; climate change; biosphere; Milky way;
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1. Introduction

The idea that energetic particles born in the aftermath of exploding stars can affect Earth thousands of light-years away may be difficult to comprehend. However, this conclusion is emerging after almost three decades of research. Not only is the climate responding, but life itself also appears to be influenced by changes in the flux of energetic particles, called cosmic rays. We are now at a pivotal point where research can provide consistency between theory, observations and experiments. In particular, we can now test the theory in a global circulation model that includes both greenhouse gases and cosmic rays, which may shed light on the climate's sensitivity to CO₂. This note provides a concise explanation of the mechanism linking cosmic rays to cloud formation, and presents examples of this relationship across time scales from days to millions of years.

2. The Mechanism

Cosmic rays are atomic nuclei accelerated to high energies in the aftermath of explosions of large stars, called supernovae. These energetic, charged particles travel through interstellar space, and some enter our solar system, where the solar wind's magnetic field modulates them before they reach Earth's atmosphere. Once in the atmosphere, cosmic rays create a shower of secondary particles that ionise the air.

Ionisation by cosmic rays plays a key role in cloud formation. The ions help gas molecules stick together to form tiny clusters, about 1-2 nanometers in diameter. These clusters, known as aerosols, can grow by absorbing gases or by colliding with other aerosols. Once they reach about 50 nanometers, they help clouds form by providing a surface for water vapour to condense on. This process usually happens when air rises and cools, leading to cloud droplets. Figure 1 overleaf illustrates the process from gas molecules to clouds.

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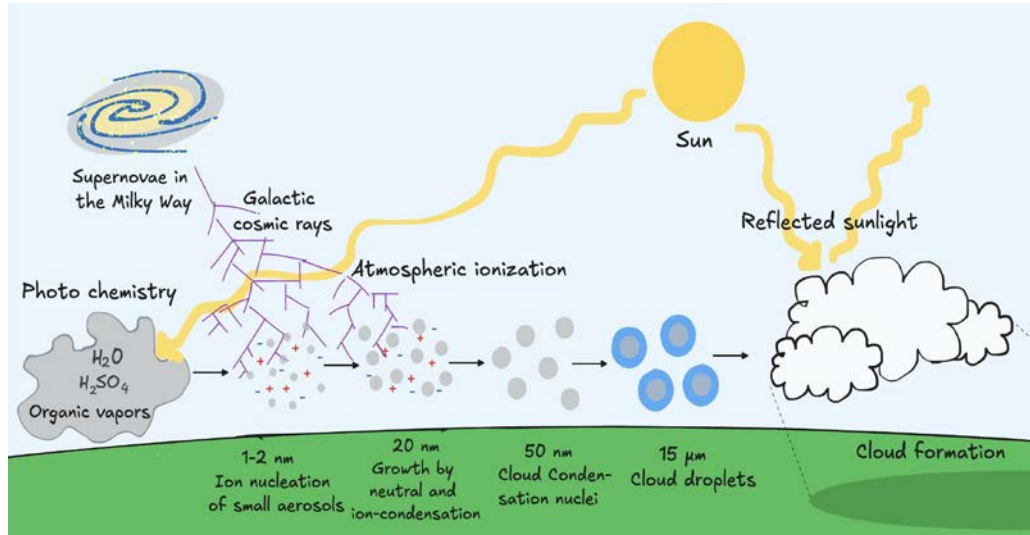


Figure 1: Illustration of cosmic ray cloud mechanism. Secondary cosmic ray particles ionise Earth's atmosphere. Ions help stabilise small molecular clusters of 1-2 nanometers and assist their growth into cloud condensation nuclei of ~50 nanometers. At this size, they can be activated as cloud droplets. The number of cloud condensation nuclei determines the radiative properties of clouds and ultimately influences the global climate.

The main idea is that as cosmic-ray ionisation increases, more cloud condensation nuclei form. For clouds, this means more cloud droplets, with smaller droplets, which makes clouds whiter and longer lasting. As a result, clouds alter the amount of energy Earth receives from the Sun. A systematic shift in cloud cover will change the climate.

3. Evidence for the cosmic ray cloud link

Experiments have confirmed that ions promote the formation of small aerosols (1-2 nanometers in diameter) from naturally occurring gases in the atmosphere [Svensmark *et al.*, 2007; Kirkby *et al.*, 2011]. In addition, ions accelerate their growth [Svensmark *et al.*, 2013; Svensmark *et al.*, 2017], making it more likely that these aerosol particles will become cloud condensation nuclei and influence cloud formation.

Observations have verified that the process shown in Fig. 1 occurs in Earth's atmosphere. For example, when the Sun ejects a charged plasma cloud that temporarily screens out cosmic rays for a week, we observe changes in aerosols, cloud properties, and Earth's energy balance [Svensmark *et al.*, 2009; Svensmark *et al.*, 2016, 2021]. Figure 2 overleaf shows an example of a clear response in aerosols and in low liquid clouds.

Both observational data and theoretical analyses indicate that the mechanism operates most efficiently in clean marine air, where aerosol concentrations are relatively low. In contrast, over land, where aerosol abundance is higher, the effect is small.

Recently, we added the ion mechanism to a global chemistry model that includes aerosols. We then looked at changes in cloud condensation nuclei between solar maximum and solar minimum. For the first time, our calculations matched the observed changes (in review). Earlier attempts did not achieve this because they overlooked the important effect of ions on accelerating aerosol growth [Kazil *et al.*, 2006; Pierce and Adams, 2009; Snow-Kropla *et al.*, 2011; Yu and Luo, 2014; Dunne *et al.*, 2016; Gordon *et al.*, 2017; Pierce, 2017].

The next step in this project is to add the ion mechanism to a Global Circulation Model. This will allow a study of how both changes in cosmic rays and anthropogenic greenhouse gas levels affect

the climate system in the 20th and 21st centuries. In particular, it will provide an estimate of the climate sensitivity to CO₂.

The following presents examples of the many apparent implications of the cosmic-ray-cloud link.

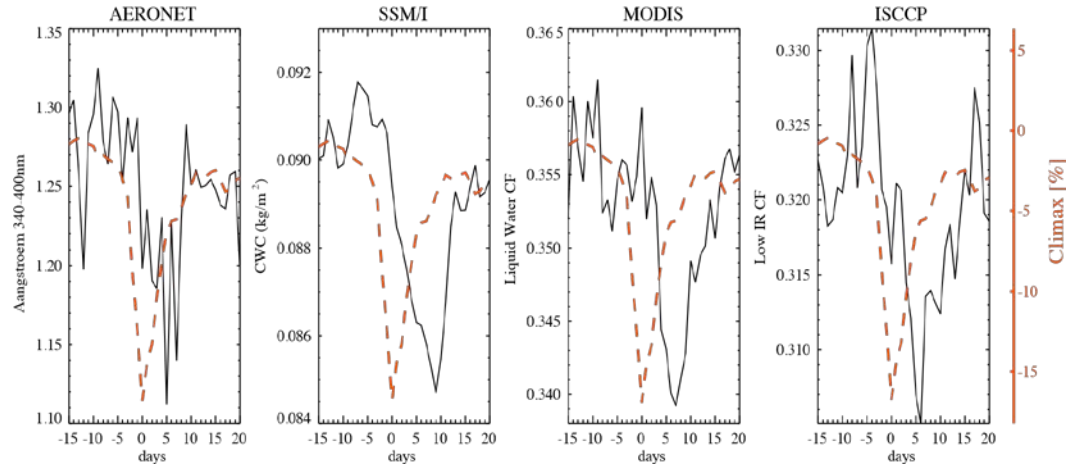


Figure 2: The daily averages of various aerosol and cloud parameters preceding and during Forbush decreases in the cosmic ray flux, averaged over the 5 strongest events between 1990 and 2005. The orange dashed line is the change in cosmic rays, and the black curves are (a) AERONET data indicating the density of aerosols in the atmosphere, (b) cloud water content (SSM/I dataset), (c) liquid water cloud fraction (MODIS dataset), and (d) low clouds (ISCCP dataset). The delay between the minimum and black curves reflects the time it takes for aerosols to grow to cloud-condensation-nucleus size. From [Svensmark et al., 2009].

4. Millennial climate change

An indication of the importance of the above mechanism is the strong correlation between climate and cosmic-ray changes over the last 10,000 years. It seems that each time cosmic rays change, climate changes in response.

Figure 3 overleaf presents temperatures and cosmic ray fluxes during the last thousand years. The top and bottom panels show a clear association between temperature variations (blue curve, top panel) and changes in cosmic ray flux (orange and green curves, bottom panel), both influenced by solar activity. Solar activity minima are evident in the blue temperature curve. The cosmic ray axis is inverted: higher cosmic ray flux corresponds to colder temperatures, while lower flux corresponds to warmer temperatures. To demonstrate the global nature of the solar-climate relationship, temperature reconstructions from worldwide borehole data are included (top panel, grey curves). As heat diffuses slowly into the ground, temperature profiles at various borehole depths provide insights into historical surface temperatures [Huang et al., 2008]. These data indicate that the peak of the Medieval Warm Period was approximately as warm as, or slightly cooler than, the 1960-1990 reference level, while the coldest phase of the Little Ice Age was about 2 °C below present temperatures.

Another beautiful example is that of a multi-millennial correlation between the temperature of the Indian Ocean as mirrored in the ratio between different oxygen isotopes in stalagmites in a cave in Oman, and solar activity, as reflected in the cosmogenic carbon-14 isotope produced by cosmic rays [Neff et al., 2001, see Figure 4 overleaf]. Another impressive result over the same timescale is that of Bond et al. [2001], which compares solar activity with the Northern Atlantic climate, as recorded on the ocean floor via ice-rafted debris. Many other correlations exist at other locations

worldwide.

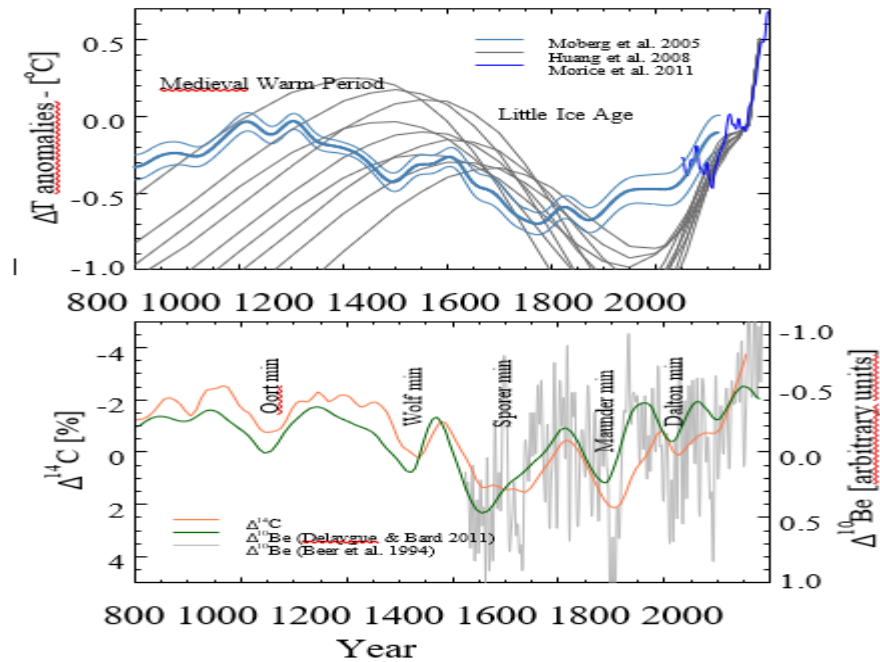


Figure 3: Comparison of variations during the last millennium of (a) temperature (with respect to the 1960 - 1990 average), (b) galactic cosmic rays (note the inverted scale; high cosmic ray fluxes are associated with cold temperatures).

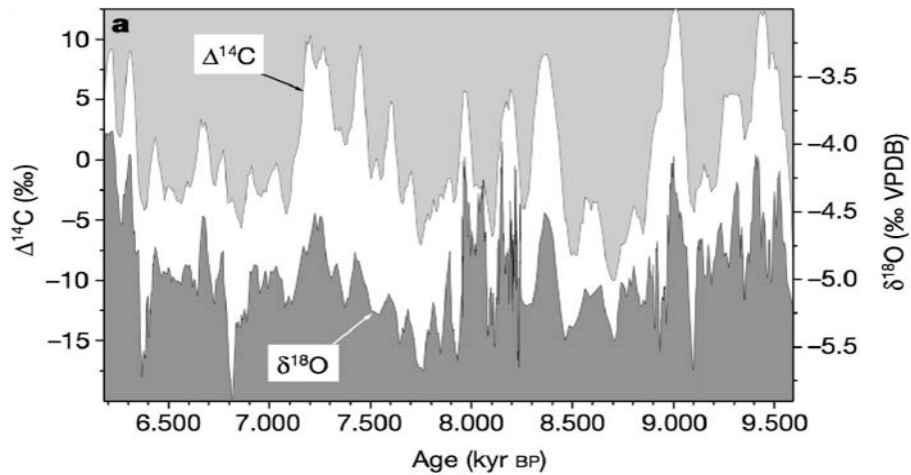


Figure 4: Climate change from a cave in Oman over a period of about 3000 years. The dark grey curve is a proxy for climate change, based on Indian Ocean surface temperature (as inferred from $\delta^{18}\text{O}$ in stalagmites). The light grey curve is the change in cosmic rays caused by solar activity (^{14}C is formed by nuclear interaction between cosmic rays and the atmosphere). From [Neff et al., 2001].

5. Climate over millions of years

The solar system orbits the centre of the Milky Way with an approximate period of 230 million years. On that journey, the solar system enters and exits regions of increased star formation that mainly occur in the Milky Way's spiral arms. Since star formation in the spiral arms also produces

massive stars that explode as supernovae after relatively short lifetimes, the spiral arms are regions of elevated cosmic ray flux. The changes in cosmic rays over millions of years provide a test of the cosmic-ray climate link independent of solar activity, and even here, remarkable agreement is observed [Shaviv, 2002; Svensmark, 2012].

Approximately 150 million years ago, the solar system was located in the Scutum-Crux spiral arm and experienced elevated cosmic ray flux (see Fig. 5). Then, 70 million years ago, the solar system was positioned between the Scutum-Crux and Sagittarius-Carina spiral arms, during which cosmic ray flux was low, and Earth's temperature was about 10 °C higher than present, resulting in an ice-free planet without polar ice caps. As the solar system approached the Sagittarius-Carina spiral arm, cosmic-ray intensity increased, leading to a cooler climate. About 34 million years ago, an ice cap formed in Antarctica. Figure 6 overleaf illustrates a remarkable correlation between changes in supernova frequency (red curve) and reconstructed temperatures (grey and cyan circles) over the past 200 million years, with temperature increasing from top to bottom on the y-axis. The supernova frequency is derived from star formation rates in open stellar clusters (red curve) [Svensmark, 2012]. The supernova rate and temperature show notable agreement, particularly regarding the onset of Antarctic glaciation, the partial thawing of the ice sheet, and subsequent re-glaciation.

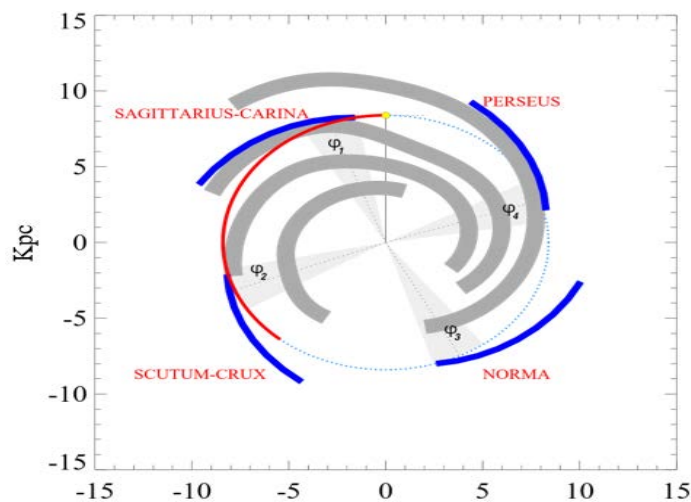


Figure 5: Illustration of the spiral structure of the Milky Way. The observed spiral arms are shown as thick grey bands and are where star formation mainly occurs. The blue arms represent the slight delay before massive stars explode as supernovae and are regions of elevated cosmic-ray flux. The yellow dot is the current position of the solar system, and the thin red line is its trajectory over the past approximately 200 million years, during which it has passed through two spiral arms. This journey in and out of spiral arms is recorded in Earth's climate as can be seen in Fig. 6 (Figure adapted from Svensmark [2012]).

As is well known from geological studies, and as exemplified in Fig. 6 overleaf, Earth's climate has changed substantially, from periods much warmer than now to severe glacial periods with huge ice sheets, and in concert with cosmic ray changes. Such large climate variations are expected to impact the conditions for life. In fact, changes in supernova rates played a role in shaping life on Earth. It can be shown that the fraction of organic material buried in sediments mirrors variations in supernova rates; see Fig. 7, two pages down. The proposed explanation is that a high supernova rate results in thicker cooling cloud cover and thus a colder Earth. A colder Earth has a larger temperature difference between the equator and the poles and stronger winds. Stronger winds increase ocean circulation, thereby increasing the flux of dissolved nutrients to living organisms. An elevated nutrient supply raises biomass, and, finally, a larger fraction of dead organic

material is sedimented on the seabed. A fundamental consequence of burying organic material in sediments is that it is a source of oxygen. As is well known, photosynthesis produces oxygen by combining water, CO₂, and sunlight to form glucose and oxygen; however, for the reaction not to reverse and turn O₂ back into CO₂, it is necessary to move organic material into sediments. Therefore, the supernova rate in the Milky Way has indirectly controlled oxygen production throughout Earth's history, and oxygen underpins complex life [Svensmark, 2022].

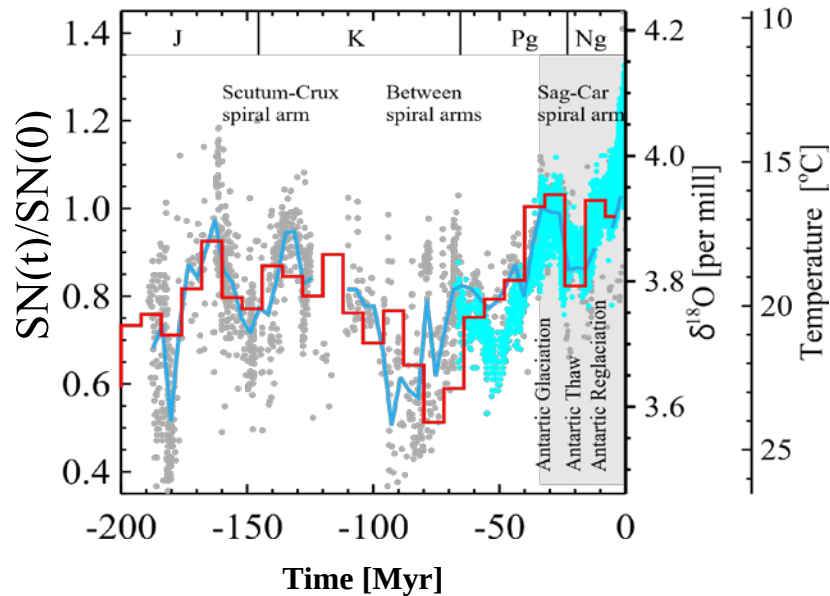


Figure 6: The evolution of Earth's temperature in the last 200 million years is inferred from measurements of $\delta^{18}\text{O}$ in fossils (planktonic foraminifera (cyan circles) and brachiopods (grey circles)). The red curve is the change in the supernova rate based on open star clusters [Svensmark, 2012]. Sag-Car is the Sagittarius-Carina spiral arm. Note that temperature increases downwards.

Supernova rates affect not only bio-productivity; they also seem to affect the diversity or richness of life. The best evidence of life's diversity comes from millions of fossils in geological sediments and is recorded in large databases. Two main influences have dominated ocean diversity over the last 500 million years: changes in supernova frequency and changes in the area of shallow marine margins (depth < 200 m) [Svensmark, 2023]. A larger area typically gives rise to greater diversity, and this has long been recognised in biology. Shallow marine margins are relevant because almost all marine life resides here. The surprise is that the supernova frequency also had a decisive effect on diversity. Figure 8 overleaf illustrates the influence of supernovae on ocean biodiversity since the Cambrian period 541 million years ago (Richness of life normalised with changes in the shallow-water area). The black curve shows supernova frequency, and the coloured curves show different extractions of genera from paleo databases, normalised to two different reconstructions of shallow-water areas along the continents. This result sheds new light on an otherwise unanswered question in evolutionary theory: why the diversity of life has varied over time.

If these results are generally accepted, they will fundamentally shift thinking from seeing the solar system as primarily isolated to understanding how processes in and around the Milky Way have helped shape life on Earth.

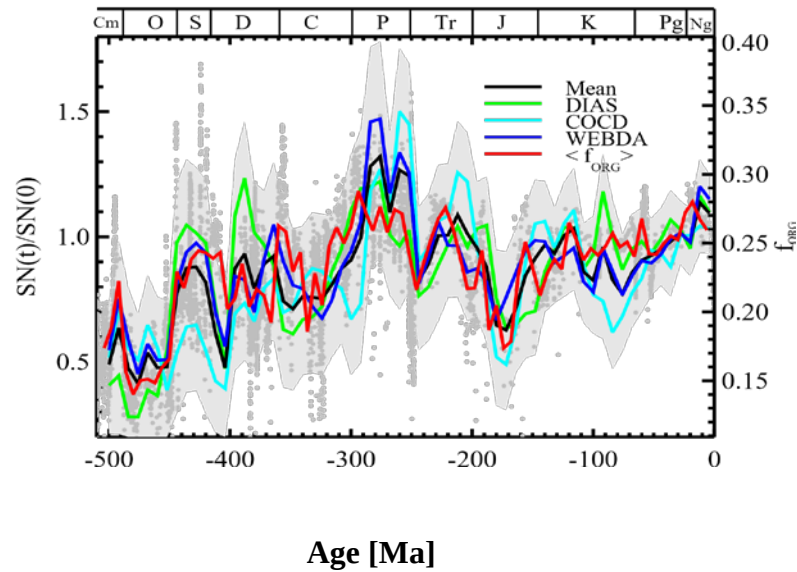


Figure 7: Illustration of the correlation between supernova frequency (green, cyan, and blue curves are based on three astrophysical datasets, and the black curve is the mean of the three datasets) and the fraction of organic material (red curve) buried in sediments over the last 500 million years (for details, see [Svensmark, 2022]).

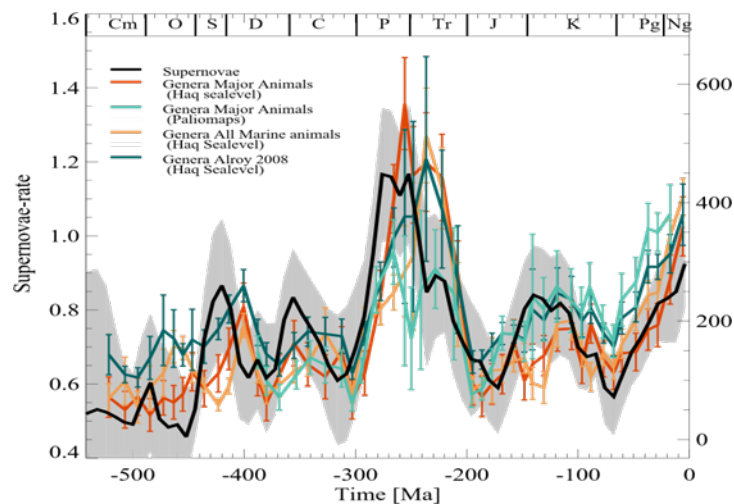


Figure 8: The change in supernova frequency (black curve) over 500 million years compared to changes in diversity (richness of life) (dark brown, light brown, dark green and light green curves). Diversity is normalised by the area of shallow-marine margins. For details, see [Svensmark, 2023]

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