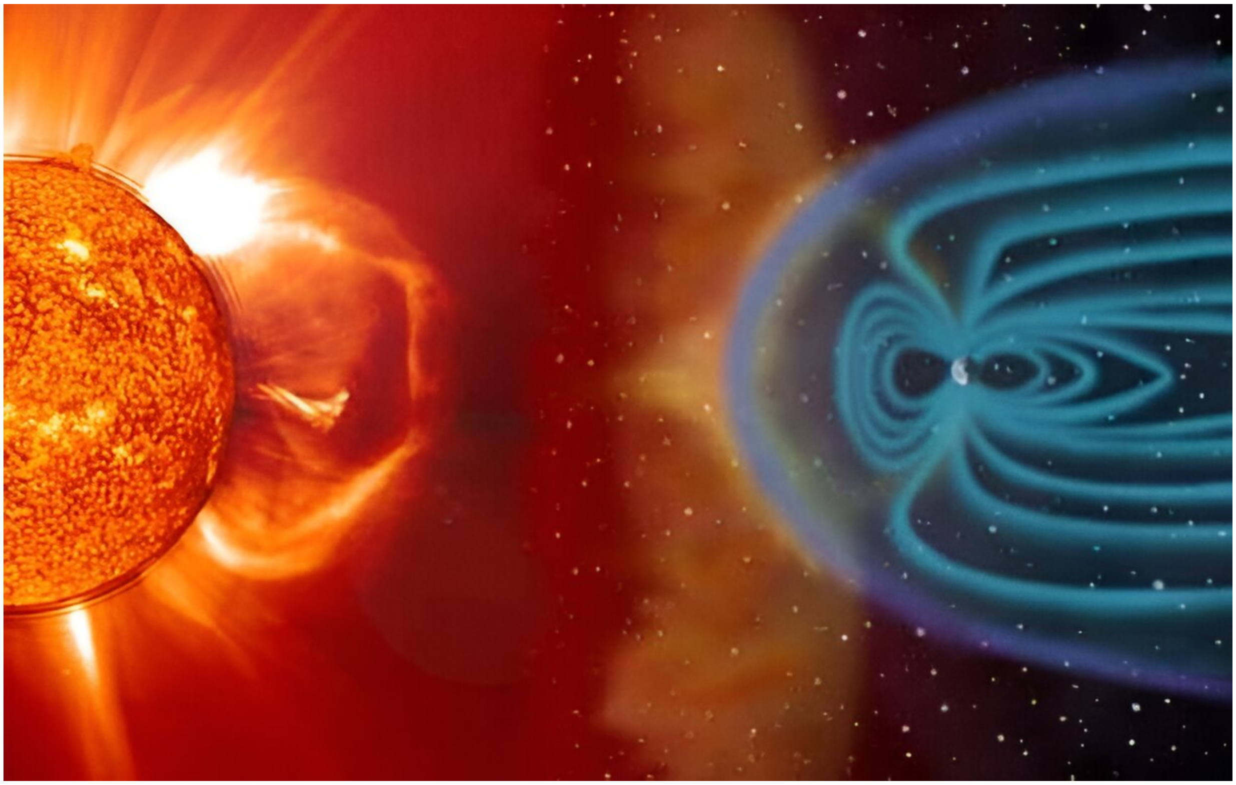
Earth's past and future habitability depends on our protection from space weather

November 16 2023, by Evan Gough



This visualization depicts what a coronal mass ejection might look like as it interacts with the interplanetary medium and magnetic forces. Credit: NASA / Steele Hill

A bewildering number of factors and variables led up to the planet we occupy today, where life finds a way to survive and even thrive in the most marginal conditions. The sun is the catalyst for it all, propelling life on its journey to greater complexity with its steady fusion.

But the sun is only benign because of Earth's built-in protection, the magnetosphere. Both the sun and the magnetosphere have changed over time, with each one's strength ebbing and flowing. The sun drives powerful space weather our way, and the magnetosphere shields the Earth.

How have these two phenomena shaped Earth's habitability?

A new study takes a look at how the sun and the Earth's magnetic shield have changed over time and how the changes affected our planet's habitability. Its title is "On Earth's habitability over the sun's main-sequence history: joint influence of space weather and Earth's magnetic field evolution." The lead author is Jacobo Varela, a researcher at the University de Carlos III de Madrid. The paper will be published in the *Monthly Notices of the Royal Astronomical Society* and is currently available on the *arXiv* preprint server.

We know a lot more about the sun than we did even a few decades ago. The Parker Solar Probe, the Solar and Heliospheric Observatory (SOHO), the Solar Dynamics Observatory (SDO) and other spacecraft are all currently studying it intensely. We know that the sun has an 11-year cycle and that it sometimes emits powerful solar storms that can knock out electrical equipment on Earth.

We also know a lot about Earth's magnetosphere. We know the planet's rotating iron core and its convection currents create a protective magnetic shield that blocks most of the sun's dangerous radiation while allowing warmth in. We know that the Earth's poles can flip positions and that the magnetosphere's strength has changed over time.

How have all these factors governed Earth's habitability?

The sun's solar wind (SW) and interplanetary magnetic field (IMF) combine to create space weather, and habitability depends on how the space weather interacts with our magnetosphere. Without a strong magnetosphere, the Earth is unprotected.

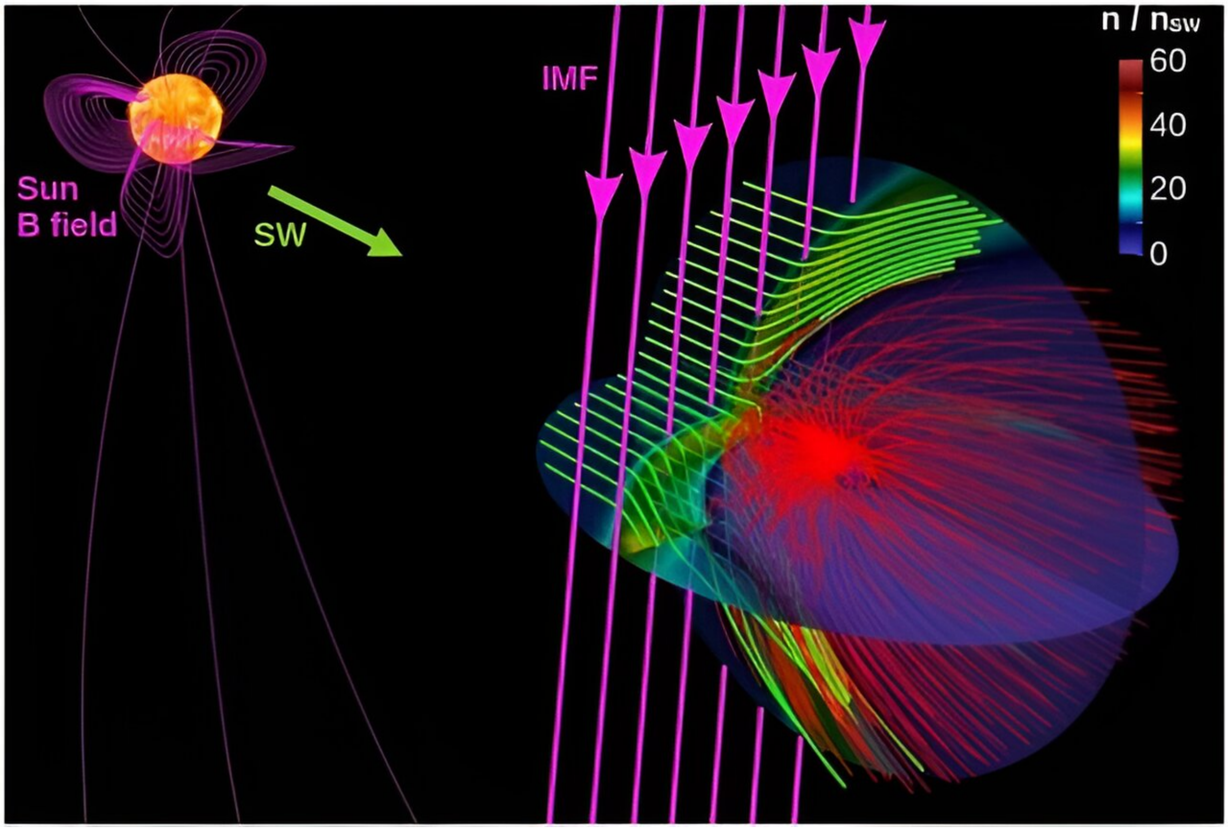
"That means space weather conditions can introduce constraints on the habitability of the Earth and exoplanets with respect to the shielding provided by planetary magnetospheres, avoiding the sterilizing effect of the stellar wind on the surface," the authors explain.

Coronal mass ejections (CMEs) have the most disruptive effect on Earth's magnetosphere. When the sun emits a powerful CME that strikes Earth, it temporarily deforms Earth's magnetosphere. The day side is compressed, and the night side is extended. Most of the time, it results only in more powerful auroras, a natural light show that reaches lower latitudes than usual.

But this is a balancing act that isn't always balanced. Earlier in the sun's history, it rotated more quickly and had more powerful magnetic activity. Since CMEs are driven by the sun's behavior, including rotation and magnetism, the sun emitted more powerful CMEs in the past. "The SW dynamic pressure and IMF intensity were much higher at earlier stages of the sun main sequence compared to the present days," the authors write, "thus, the perturbations induced by the young sun on the Earth's magnetosphere were stronger."

The question is, how exactly did this all change over time, and how did it affect habitability? How will it affect it in the future?

"The aim of the present study is to analyze the Earth's habitability along the sun's evolution on the main sequence," the authors explain. The team performed a series of detailed simulations to probe the interplay between the sun and the Earth over billions of years of history. The simulations are based on established scientific models of factors like the SW's strength over time.



This schematic from the study shows a typical simulation setup. The green arrow and lines are the sun's solar wind (SW), the pink lines are the sun's interplanetary magnetic field, also called the heliospheric magnetic field (HMF), and the red lines are the Earth's magnetic field lines. The colour scale shows the SW's density distribution. Credit: Varela et al. 2023

One of the things that changes over time is the Earth's magnetic field strength, measured in microteslas. Recent evidence shows that it changes according to a 200 million-year cycle. The changes are driven by changes inside the Earth, where the field is generated.

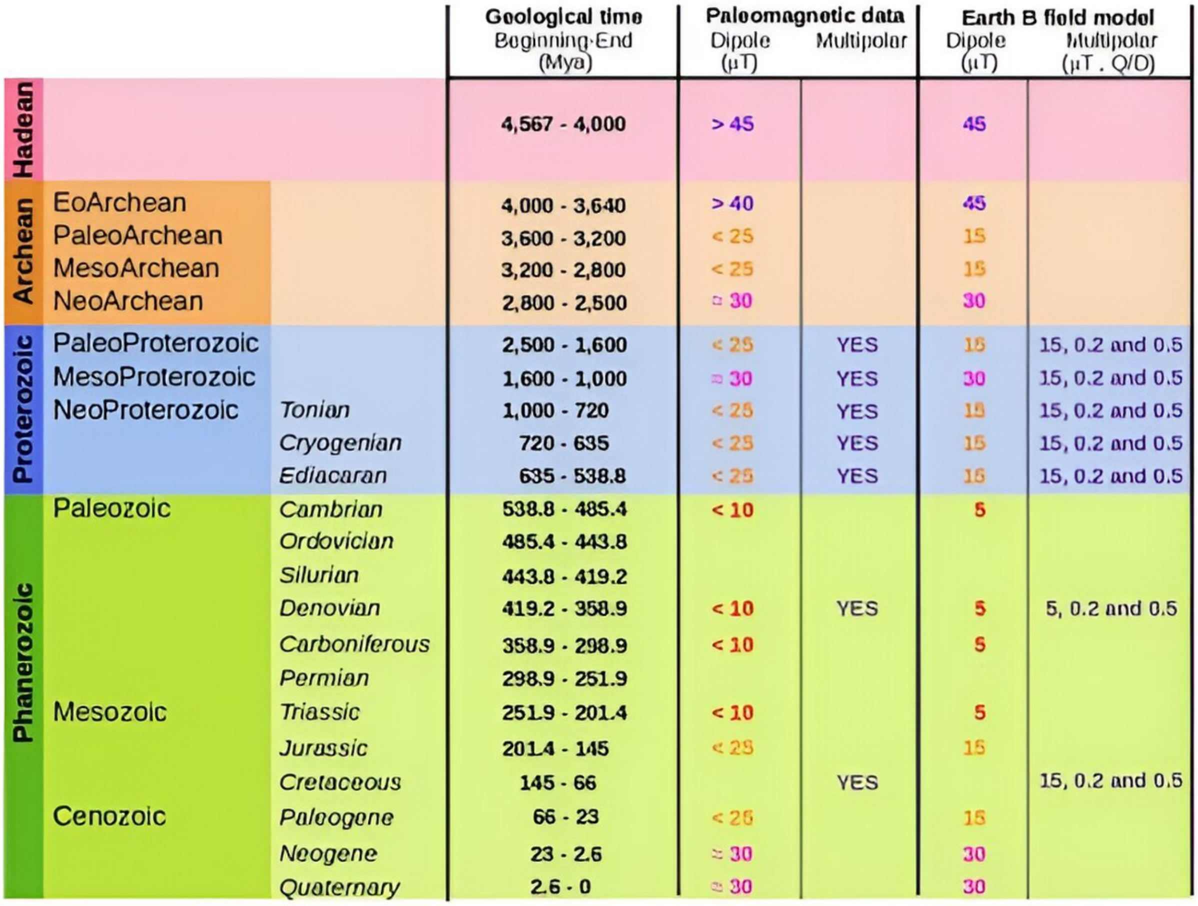
The authors examined how Earth's habitability changed during periods of weak, normal, and high dipolar magnetic field intensity.

Earth also had periods where the nature of its magnetic field changed, not just its intensity. Occasionally, Earth experiences periods of time when its magnetic field is multipolar rather than dipolar. The field's strength also varies at these times, and when it's weak, the field can reverse.

The figure below shows some of the data used in the simulations. The team used models for four different intensity ranges in Earth's magnetic field. They're shown in the two columns labeled Dipole under the paleomagnetic data column and the Earth B field model column.

Earth experienced low field intensity throughout the Proterozoic eon and during the Cambrian, Denovian and Carboniferous periods in the Paleozoic era. There was also low field intensity in the Triassic period during the Mesozoic. Those times correspond to models with only 5 microteslas, shown in red.

Slightly stronger 15 microtesla periods occurred during the Paleo-Archean and Meso-Archean eras, Proterozoic eon, Jurassic period in the Mesozoic era and the Paleogene period in the Cenozoic era. Those are shown in orange under the Dipole columns.

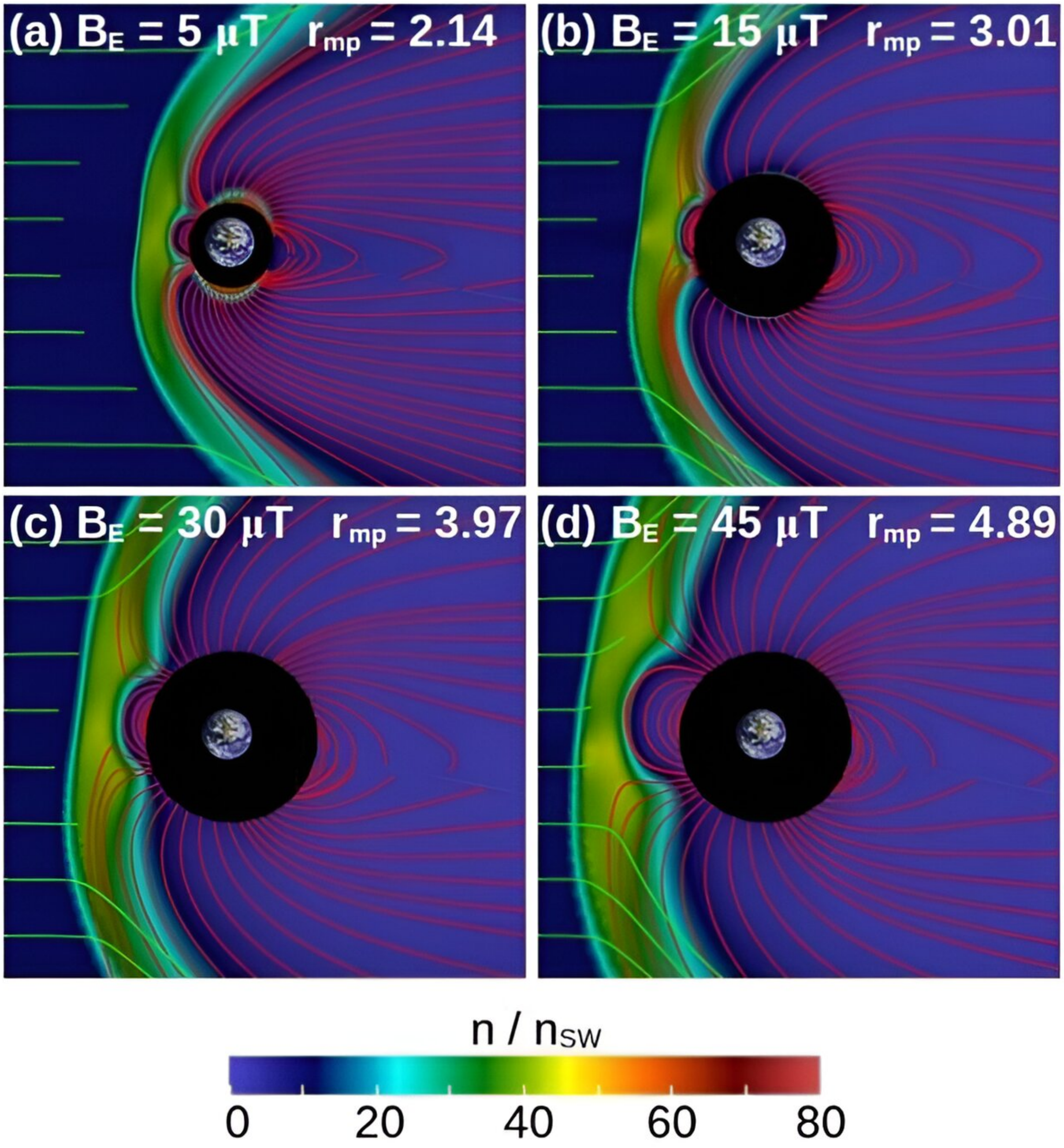


			Geological time	Paleomagnetic data		Earth B field model	
			Beginning-End (Mya)	Dipole (µT)	Multipolar	Dipole (µT)	Multipolar (µT . Q/D)
Hadean			4,567 - 4,000	> 45		45	
Archean	EoArchean		4,000 - 3,640	> 40		45	
	PaleoArchean		3,600 - 3,200	< 25		15	
	MesoArchean		3,200 - 2,800	< 25		15	
	NeoArchean		2,800 - 2,500	≃ 30		30	
Proterozoic	PaleoProterozoic		2,500 - 1,600	< 25	YES	15	15, 0.2 and 0.5
	MesoProterozoic		1,600 - 1,000	≃ 30	YES	30	15, 0.2 and 0.5
	NeoProterozoic	*Tonian*	1,000 - 720	< 25	YES	15	15, 0.2 and 0.5
		Cryogenian	720 - 635	< 25	YES	15	15, 0.2 and 0.5
		Ediacaran	635 - 538.8	< 25	YES	15	15, 0.2 and 0.5
Phanerozoic	Paleozoic	*Cambrian*	538.8 - 485.4	< 10		5	
		Ordovician	485.4 - 443.8				
		Silurian	443.8 - 419.2				
		Denovian	419.2 - 358.9	< 10	YES	5	5, 0.2 and 0.5
		Carboniferous	358.9 - 298.9	< 10		5	
		Permian	298.9 - 251.9				
	Mesozoic	*Triassic*	251.9 - 201.4	< 10		5	
		Jurassic	201.4 - 145	< 25		15	
		Cretaceous	145 - 66		YES		15, 0.2 and 0.5
	Cenozoic	*Paleogene*	66 - 23	< 25		15	
		Neogene	23 - 2.6	≃ 30		30	
		Quaternary	2.6 - 0	≃ 30		30	

This table from the research shows how the Earth's magnetic field strength has fluctuated over its history. Credit: Varela et al, 2023

"The dipole model with 30 μT illustrates the Meso-Proterozoic and Neo-Archean eras, as well as the Neogene and Quaternary periods in the Cretaceous era," the authors explain. Those times are shown in pink.

Earth's magnetic field strength was at its strongest during its early days. "The dipole model with 45 μT represents high field periods during the Hadean eon and the Eo-Archean era," the authors write. Those are shown in purple.



This figure from the research shows how the Earth's dipole strength pushes against the solar wind. The stronger the dipole, the more difficult it is for SW to reach Earth's surface. (a) is 5 µT, (b) is 15 µT, (c) is 30 µT and (d) is 45 µT. The red lines show the Earth's magnetic field and the green lines show the SW velocity stream lines. Image Credit: Varela et al, 2023

So what does this all add up to?

A critical part of this work is the magnetopause standoff distance. That distance is compressed by more energetic solar winds and expanded when the Earth's magnetic strength is higher. In the figure above, (a) has a much-reduced magnetopause standoff distance than (d) when the magnetic field strength is higher.

During times of powerful solar winds and weaker magnetism, the magnetopause standoff distance is closer to Earth's surface, meaning the sun poses a threat to life. If that distance is reduced to zero, meaning the sun's radiation can directly reach the surface, then Earth's habitability is severely reduced.

"We conclude that the hamper of space weather on the Earth's habitability must be considered as an important driver of the atmosphere and life evolution," the authors write. (Please note that English is not the authors' first language and that their syntax reflects that. Nonetheless, the meaning is clear.)

The research shows how space weather and the Earth's magnetic field strength have both changed over time and contributed to habitability or made habitability more difficult. It shows, in particular, that when Earth is in a multipole configuration, prior to pole reversal, we're more susceptible to space weather. The last pole reversal took place about 780,000 years ago, and the magnetic shield was weakened. Reversals can take hundreds or even thousands of years. We're still protected during reversals, but not as well. If a powerful CME struck during this time, it could trigger a massive geomagnetic storm.

In the distant future, Earth's dipole will weaken. Its geodynamo will fade away, much like Mars' has. The planet will be less able to resist the sun's output, and habitability will cease to be. Eventually, successive ICMEs will strike the surface, wreaking havoc on Earth's biosphere. In time, even relatively weak solar wind will reach the surface, and Earth will be continually bathed in radiation.

But for now, we're okay. We can go about our business slowly degrading Earth's habitability without any help.

More information: J Varela et al, On Earth's habitability over the Sun's main-sequence history: joint influence of space weather and Earth's magnetic field evolution, *Monthly Notices of the Royal Astronomical Society* (2023). DOI: 10.1093/mnras/stad2519. On *arXiv*: DOI: 10.48550/arxiv.2311.03720

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