Nexus
Perspective

Immortal AI, space radiation, and materials science

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BROADER CONTEXT

In this perspective, we extend the connection between artificial intelligence and energy use to the context of space exploration. Radiation tolerance and timescale of space travel put biology at a disadvantage for deep space exploration compared to hard materials-based artificial intelligence systems that can evolve autonomously in space, driven by nuclear energy. For these reasons, Earth is very special and must be preserved for organic life.

SUMMARY

The rapid development of artificial intelligence (AI) based on electronic hardware and the field of AI for science and autonomous experimentation raises the question of how far AI can go in the longer time horizon. Can AI supersede biological intelligence? Will electricity production limit AI? This article is a speculative discussion based on current scientific knowledge, aiming to explore the physical limits of biological and artificial intelligence in interstellar colonization. It is shown that the intrinsic limitations of biology would make it exceedingly difficult to escape Earth, whereas embodied AI powered by nuclear energy would not be similarly constrained. A key timescale of 10^5 years is required to travel to the hundred nearest exoplanets at a speed that is feasible with today's technology and matches the energy scale provided by breeder nuclear reactors. Nuclear materials science and recycling are keys in this endeavor, which may be accomplished by embodied AI agents or "AIiens." The ethics of AI and sociopolitical consequences are fundamental challenges. Earth is unique and must be preserved for organic life.

BIOLOGY'S ESCAPE BARRIER IS HIGH

Despite frequent portrayals of manned space travel in the popular culture, there are extreme barriers against humans traveling beyond low-Earth orbit. Space radiation—charged particles ∼10MeV to 10GeV in energy, and even higher from galactic cosmic rays—induces a radiation dose on the order of sieverts for a 2.5- to 3-year-long round trip to Mars,[1] already close to the fatal limit for human beings. The geodynamo effect protects our Earth, as the magnetic field generated by Earth's circulating molten iron core shields us from the charged particles, giving rise to the beautiful auroras. But, recreating such protection for manmade vehicles is extremely difficult. Active shielding by an artificial superconducting magnet or passive shielding would require exorbitant power or weight. One also has to wait 1.5 years on Mars for a favorable planetary alignment for the return journey, and the thin atmosphere and extreme temperatures (as low as −150°C) on Mars would be very unforgiving to humans or most animal or plant life.

Bone loss and psychological duress would make any trip longer than a few years away from Earth very unpleasant for humans, whereas space colonization requires millennia to megayears (Myr), as the simple calculations below show. While there exist more than 100 known exoplanets located within 10 parsecs (∼32.6 light-years) from Earth, it is well beyond the current technological envelope to bring humans to those exoplanets, in "Noah's Ark" fashion.

EMBODIED ARTIFICIAL INTELLIGENCES' ESCAPE BARRIER IS LOW

On the other hand, embodied artificial intelligences (AIs)[2] based on inorganic materials (silicon, metals, etc.) have a relatively lower barrier of entry into deep space, likely already within the technological envelope by mid-century. Simply put, many devices can be made to work better and longer in vacuum and −150°C than in a moist and oxidative atmosphere. As far as radiation tolerance is concerned, the training of deep neural networks is already based on stochastic algorithms. Occasional radiation-induced faults, ameliorated by error correction codes, system redundancy (e.g., a committee of computers), and software techniques would not be catastrophic.[3,4] To achieve immortality, the hardware just needs periodic annealing to repair the space-radiation-induced damage and other forms of wear and tear. Embodied AI agents, or "AIiens," can also resynthesize new materials[5] in space, by melting, re-solidification, and purification type extractive metallurgy. All that's needed is a *very* long-term energy source, which can be provided by nuclear fission and/or fusion.[6] While fission power reactors are more mature, fusion reactors use lighter fuels, which are advantageous for space propulsion. Heat sink is provided by radiative heat transfer to the cosmic microwave background at 2.7 K.

Given the contrast in barriers to space travel between living fauna/flora and inorganic devices, and the recent rapid advances in AI and automation,[5] it appears inevitable that space colonization will be physically achieved by AI-based inorganics first, instead of humans. (It is indeed possible to have cyborgs, but for the purpose of classification, we choose not to call them humans.) An essential characteristic of humans is that human individuals die, erasing memories of the past. In contrast, exact copying of the digital memory, and thus cloning of AI instances or agents, is achievable, and such immortal AIs are fundamentally different from humans and more well suited for 10^5-year travels. This raises fundamental ethics and economic and sociopolitical concerns for those on Earth.

ENERGY EFFICIENCY OF AI

The present generation of computing hardware is energy inefficient due to the need to transport bits between memories and processors in the von Neumann architecture. Due to the voracious electrical energy requirements, in 2024, big companies like Microsoft, Google, and Amazon are utilizing grid-scale battery energy storage[7] and nuclear energy to power the AI data centers.[8] In September 2025, OpenAI projected a need for 250 GW of computing by 2033, which is 1/5 of all the electricity production in the United States, just for one company.

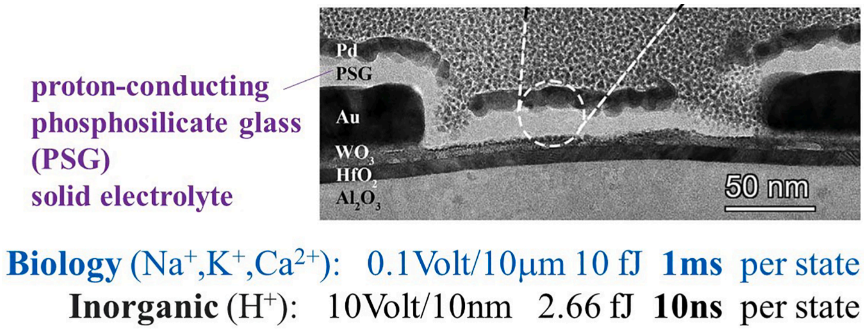

Figure 1. An all-solid-state neuromorphic ionic synapse device
A comparison in performance with water-based biological ionic channels is made. Taken from Onen et al.[10] This field is still exploratory, with several startup companies working on demonstration prototypes.

Will electricity supply limit AI? Chess master Kasparov's brain consumes 20 W of power, while IBM's Deep Blue required kilowatts, and artificial general intelligence powered by today's GPUs requires megawatts of electricity to train. So, it appears that the availability of electrical energy may constrain AI growth.

But, the GPU-based AI is likely just the first version of AI hardware. It has been only 79 years since ENIAC, a mere blip when viewed at the historical 0.3-Myr timescale of *homo sapiens*. Inspired by the physical foundation of biological intelligence, which is the transport of Na^+, K^+, Ca^{2+}, etc., ions in neuronal cells across nanometer-scale hydrated ion channels, researchers are developing neuromorphic *inorganic* ionic channels[9] that would enable in-memory parallel computing, which is orders of magnitude faster but also energy efficient. The field of neuromorphic computing is undergoing rapid development, and its use in deep space[4] is driven by the very limited amount of electrical power available for deep space travel, so far.[6]

SCALING OF BIOLOGICAL INTELLIGENCE VERSUS MACHINE INTELLIGENCE

However, even in the realm of neuromorphic computing, water-based biology is inherently limited. Due to the electrochemical stability of liquid water and the requirement of homeostasis (pH, temperature, etc.), the maximum action potential that can be applied across biological ion channels can only be ~0.1 V. This basic limitation restricts the magnitude of electromotive force in biological ionics, which then limits the speed of ion transport and neuronal electrical signals to milliseconds timescale. This millisecond timescale of water-based neuronal ionics controls the speed of thought and reflex in *all* biological beings.

In contrast, for inorganics-based *solid-state* neuromorphic devices, as high as ~10 V can be applied across a few nanometer-thick inorganic phosphosilicate solid proton conductor, and thus the fundamental timescale of solid-state nano-ionics is nanoseconds instead of milliseconds, and the energy cost is comparable (Figure 1).[9] Modern semiconductor fabrication techniques (crystal growth, vapor deposition, lithography, etc.) already lead to devices with much smaller footprints than biological neurons and demonstrate equally energy-efficient in-memory computing (2.66 fJ per state versus 10 fJ per state in biology). By utilizing high-quality energy sources, including nuclear electricity, fast communications using photons, and nonvolatile solid-state memories, machine intelligence can be more scalable. With time, energy, and autonomous experimentations to provide fresh data,[2,11] the embodied AI agents or "Aliens" will likely reach greater heights in general intelligence than biological beings.

MATERIALS ARE TOLERANT OF EXTREME CONDITIONS IN SPACE AND CAN BE RECYCLED

Although biological self-assembly is versatile, its survivable temperature range (no more than 100°C), voltage range (water's electrochemical stability window of 1.23 V), and energy intensity (no nuclear energy utilization) ultimately limit what biology can achieve. Electron and photon-driven inorganic AIs can and will evolve faster.[5,11]

So far, little attention has been paid to the radiation tolerance of ionic neuromorphic devices,[4] which function similarly to all-solid-state batteries or electrochromic windows on Boeing 787 Dreamliners. But this is a key issue for space travel. Mammalian biology does not allow the body temperature to deviate significantly from 37°C. Stunning DNA repair and immunity mechanisms exist in biology to repair damage (and fight infections), but such mechanisms are not complete solutions. On the other hand, temperature annealing to a few hundred degrees Celsius would repair most of the damage in materials, including radiation damage (Figure 2).[12] The AIs can choose to experiment with materials science,[11] reuse/recycle,[7,13] and resynthesize new materials[2,5,11,14] physically through the melting-solidification cycle. All such autonomous intelligent systems or "Aiiens" need is a very long-endurance energy source. Nuclear energy, by being $10^6\times$ more energy dense gravimetrically than chemical energy, fits the requirement just right for traveling to the nearest exoplanets.

DEEP SPACE EXPLORATIONS POWERED BY NUCLEAR ENERGY

If fast-neutron breeder fission reactors are used, nuclear fuels of uranium and thorium can bear $\sim10^6\times$ more energy per weight than TNT. It is entirely conceivable that, powered by compact

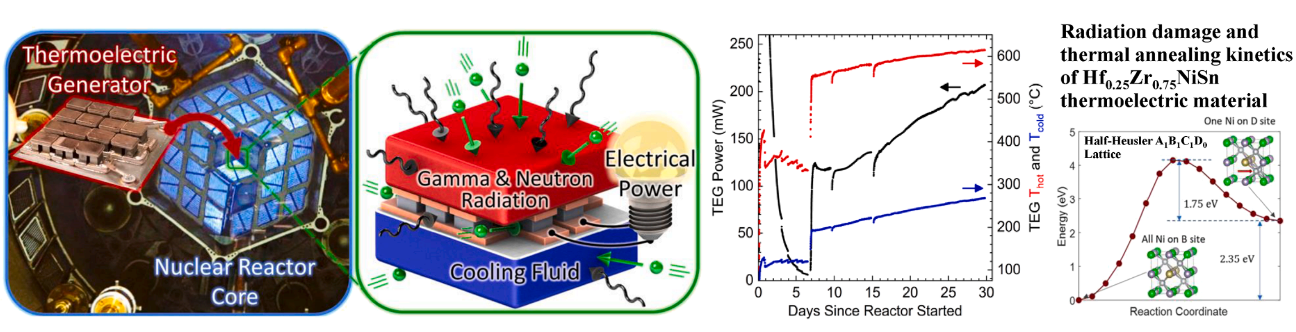

Figure 2. Thermoelectric energy generator (TEG) inside the MIT nuclear reactor core
Tungsten susceptors are heated by gamma-rays, which then drive $Hf_{0.25}Zr_{0.75}NiSn_{0.99}Sb_{0.01}$ and $Nb_{0.75}Ti_{0.25}FeSb$ n-type and p-type thermoelectrics.[12] The electrical power output dropped in the first 6 days inside the fission reactor core due to accumulation of radiation damage in the thermoelectrics, but on the 7th day, the core temperature was raised, which annealed out the radiation damage, and the TEG electric power output went back up. Taken from Kempf et al.[12]

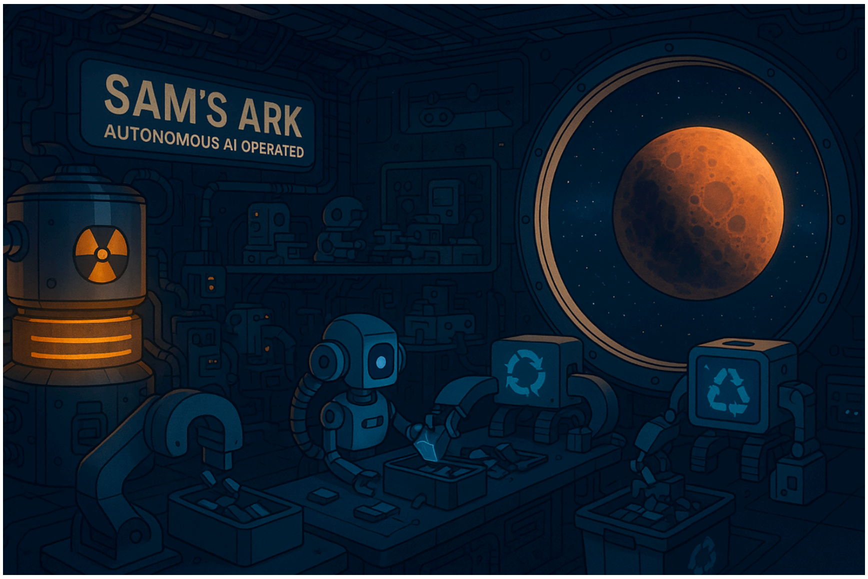

Figure 3. 10^{11} stars in the Milky Way, only 1 for humans

This cartoon was generated by ChatGPT-5.1.

nuclear fission or fission/fusion hybrid[15] reactors, a closed ecological system (CES), a "biodome" of Aiiens, can be sustained for ~Myr timescale. Indeed, the longest submarine patrol under the ocean, very similar to a CES, was ~200 days, and already, it had a compact nuclear fission reactor powering the trip. (Deep ocean has some analogy to deep space; those who want to go to Mars should first experience long submarine travel.) The erosion rate of the hull of a spaceship immersed in deep interstellar medium (including space radiation and space dust) is less than 1 μm/decade,[16] so a hull thickness of 10 cm should last ~ Myr. It just so happens that "stamina" offered by nuclear fuels matches the timescale *required* to travel to the next rocky exoplanet, where more nuclear fuels are likely to be found.

A VERY LONG VIEW

In materials science and engineering, the field of nuclear materials is quite unique in that it actually attempts to deal with Myr-scale materials phenomena[17,18] due to the stringent government-imposed requirements of permanent geological disposal of nuclear waste (there is no such requirement for the wastes of chemical energy use so far). Knowledge gained in this field, as well as materials recycling[7,13,19] and circular economy [20], could be important for colonization of the Milky Way galaxy (Figure 3).

Instead of science fiction, let us ponder what may already be achievable with today's materials technology. Aliens that can survive space radiation for 0.1 Myr would allow reaching Proxima Centauri 4.25 light-years away, with two rocky exoplanets Proxima b and Proxima d, at an average travel speed of 13.1 km/s. This speed is very achievable, given the escape velocity from Earth is already 11.2 km/s, which is the minimum energy cost of space travel (one can also use the Moon as the forward assembly base to reduce the cost and risks of launching nuclear-powered spacecrafts). Ion drive/thruster can achieve exhaust velocities of a few hundred km/s. The highest speed ever achieved by a human-made object in space is 176 km/s, by NASA's Parker Solar Probe in 2023. Barnard's Star, the 2nd closest star system, has four rocky exoplanets and is also just 5.96 light-years away, so it can be reached in 0.1 Myr if the speed is 17.7 km/s, which sounds feasible. Within the ~Myr time frame (3× *homo sapiens* history), it is therefore possible to travel to any of the 100 known exoplanets located within 10 parsecs (~32.6 light-years) from Earth and colonize them.

So, within the technology envelope of this century, Aliens could start to propagate from one solar system to adjacent ones, refuel, and multiply. Embodied AIs and replicas can endure such long travels and harsh space radiation, which would be unbearable for humans. Our Milky Way galaxy contains at least 100 billion stars and likely trillions of exoplanets, which is practically infinite, thus the namesake "Immortal AI" in the title.

But in the foreseeable horizon, Earth is the only plausible habitat for water-based biological beings. We therefore must preserve Earth from hazards such as climate change, nuclear war, and wanton inorganic AIs. The inorganic AIs can have the whole galaxy, but we humans have only Earth.

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DECLARATION OF INTERESTS

The author declares no competing interest.

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