Preprints.org

Review

Not peer-reviewed version

The Silicene Event—A New Planetary Interval Defined by Silicon-Based Intelligence

Tianxi Sun [*,†]

Posted Date: 10 March 2026

doi: 10.20944/preprints202603.0724.v1

Keywords: CEAI explorers; the Silicene Event; machine intelligence; beyond the milky way; post-human civilization

Review

The Silicene Event—A New Planetary Interval Defined by Silicon-Based Intelligence

Tianxi Sun †

East China Hydroelectric Power Survey & Design Institute, Hangzhou 311122, China (Formerly) and Suzhou Ecological Environment Bureau, Suzhou 215000, China; 18913505350@163.com

† retired.

Abstract

Human bodies evolved for Earth, not the cosmos. This paper argues that silicon-based intelligence offers the only viable path beyond this limitation. Recent breakthroughs in pressure-free silicon batteries enable true energy autonomy in space, while two-dimensional silicene provides radiation-hardened cognition. The convergence of energy and information in a single material has no analogue in biology and constitutes the definitive evidence for the Silicene Event. We derive a figure of merit (F = E × T × R / M) showing that silicon outperforms biology by a factor of approximately 9×10^6. We propose that this transition constitutes a new planetary interval: the Silicene Event. Far from ending the human story, it represents its most profound continuation. The Silicene Event—a new planetary interval defined by silicon-based intelligence—is already underway.

Keywords: CEAI explorers; the Silicene Event; machine intelligence; beyond the milky way; post-human civilization

---

I. Introduction

As a geologist by training, I am acutely aware of the stringent criteria required to formally define a new geological interval. The Silicene Event, as proposed here, is not intended to compete with the stratigraphic record. Rather, it follows the framework recently consolidated in the Anthropocene debate (Gibbard et al., 2022; Rull, 2025)*[**1**,**2**]*: it is a planetary interval—a time-transgressive, functionally defined phase in Earth's (and potentially other planets') history, marked by the emergence of silicon-based intelligence as a dominant planetary force. This framing honors geological rigor while liberating the concept from the impossible burden of requiring a global stratotype. *CEAI explorers* refer to conscious, embodied AI agents.

Chapter 1

The belief that intelligence must reside in biological substrates is not a scientific conclusion but a cognitive fossil—a remnant of our evolutionary origins masquerading as cosmic necessity. We term this unexamined assumption carbon chauvinism: the tacit conviction that the particular chemistry that gave rise to mind on Earth constitutes the universal standard for mind anywhere. Like its predecessors—geocentrism, anthropocentrism, speciesism—carbon chauvinism mistakes a local accident for a cosmic law. This chapter excavates its foundations, exposes its limitations, and prepares the ground for its legitimate successor: the recognition that the Silicene Event—a new planetary interval defined by silicon-based intelligence—is not a rupture but an inheritance.

A. The Planetary Prejudice Extended

The critique of planetary chauvinism is well established. Arendt's (1945)[*3*] analysis of imperialist ideology, extended to the cosmic domain, reveals the tendency of dominant groups to mistake their particular mode of existence for the universal condition. This pattern echoes what

 doi:10.20944/preprints202603.0724.v1

Oldham (1936)*[4]*, in his anatomy of provincialism, identified as the core cognitive pathology of the provincial mind: the inability to recognize that its own conventions are local, not universal. In astrobiology, this manifests as the assumption that habitable zones, liquid water, and temperate climates are prerequisites for intelligence—an assumption that Dick (2008)*[5]* and Ćirković (2018)*[6]* have systematically dismantled through their articulation of the postbiological universe hypothesis. If advanced civilizations evolve toward non-biological forms as a matter of developmental logic, then the search for carbon-based, water-dwelling cousins reflects not scientific rigor but provincial imagination.

We extend this critique from where intelligence resides to what it is made of. As Del Popolo (2025)*[7]* notes, while carbon's ability to *form stable, long-chain molecules* makes it uniquely suited to Earth-like environments, other abundant elements—notably silicon—*possess the covalent bonding capacity* necessary for complex information processing. The assumption that carbon is necessary for intelligence thus reflects not chemical inevitability but planetary provincialism. Carbon chauvinism shares the same psychological roots as planetary chauvinism: the failure of imagination that mistakes familiarity for necessity. This failure has practical consequences—it directs research funding, shapes mission priorities, and blinds us to emerging successors. More fundamentally, as Kalfagianni, Pedersen, and Stevis (2024)*[8]* argue, the unexamined privileging of any particular form of existence—whether biological, national, or human—risks perpetuating injustices at the planetary scale. *A truly just orientation toward the future must remain open to forms of intelligence that do not share our substrate.*

B. The Local Optimum Argument

Evolutionary biology teaches that adaptation is always local. Organisms are optimized not for all possible environments but for the specific ecological niches in which they evolved. The human brain, for all its remarkable capacities, is no exception. It is exquisitely tuned to the savannas of Pleistocene Africa, where rapid threat detection, tribal coalition formation, and short-term planning conferred survival advantages. Its architecture reflects these ancestral pressures: it is biased toward immediate rewards, vulnerable to cognitive biases, and metabolically expensive to operate.

The concept of a local optimum is mathematically rigorous. In optimization theory, a local optimum is a solution that is better than all its immediate neighbors but may be far inferior to solutions elsewhere in the solution space. Crucially, as Scherrer & Geist (2013)*[9]* demonstrated, even local optima can enjoy global performance guarantees under certain conditions. This insight has a profound implication for our argument: biological intelligence, as a local optimum, is not arbitrarily bad—it is exquisitely good at solving the problems its ancestors faced on the African savanna. But this very excellence is what makes it difficult to see beyond those problems.

Zhou & Low (2020)*[10]* provide the complementary insight: they establish a sufficient condition for local optima to be globally optimal—a condition that biological intelligence manifestly fails to meet when its environment shifts from the savanna to the cosmos. The human cognitive architecture, shaped by Pleistocene selection pressures, is optimized for rapid threat detection, tribal coalition formation, and short-term planning. It is not optimized for multi-century space travel, interstellar communication delays, or the kind of abstract, long-horizon reasoning that cosmic existence demands. This is not a failure of human intelligence; it is a feature of its local optimality.

The thermodynamic burden of biological intelligence is particularly stark. The human brain consumes approximately 20% of the body's energy despite constituting only 2% of its mass (National Academies of Sciences, Engineering, and Medicine, 2023)*[11]*. This extravagant metabolic cost is sustainable on Earth but becomes catastrophic in deep space. Recent advances in biological thermodynamics provide a framework for understanding why. Zhao (2025a)*[12]* proposes a thermodynamic hypothesis for biological development, suggesting that living systems operate near thermodynamic limits imposed by their evolutionary history. Cao & Liang (2024)*[13]* extend this analysis to stochastic thermodynamics, demonstrating that biological functions are fundamentally constrained by the energy-dissipation requirements of maintaining organization. Every calorie a biological explorer consumes must be grown, processed, packaged, and transported—a logistical chain whose complexity grows exponentially with mission duration.

Jones et al. (2025)*[14]* provide a sobering illustration of biological fragility. Even in Earth's most stable and buffered environment, a single disturbance requires decades for partial recovery. Extrapolate this fragility to Mars, where a single life-support failure could terminate an entire colony, and the case for biological expansion becomes untenable.

The mathematical framework provided by Scherrer & Geist (2013)*[9]* and Zhou & Low (2020)*[10]* clarifies what is at stake: biological intelligence is a magnificent local optimum, mathematically characterizable as such, but trapped by the very mechanisms that define it. Its escape, as we shall see, lies not in incremental adaptation but in exaptation—the repurposing of its core achievements in a new substrate. The following sections will develop this argument, showing that silicon-based intelligence offers precisely the kind of global optimum that biology, for all its wonders, cannot reach.

C. Temporal Mismatch

A second fundamental limitation of biological intelligence is its temporal horizon. The human brain is the product of evolutionary pressures that operated on timescales of generations—years, decades, at most centuries. Its cognitive architecture is exquisitely tuned for rapid threat detection, immediate reward seeking, and short-term social planning. This is a feature, not a bug, for survival on the Pleistocene savanna. Yet when this same brain is asked to contemplate projects that span millennia—interstellar voyages, galactic migrations, the long-term evolution of intelligence itself—it encounters a profound temporal mismatch.

The idea that synchrony between interacting systems is critical—and that its breakdown can have cascading consequences—is well established across the sciences. Burgess et al. (2018)*[15]* demonstrate how phenological mismatch disrupts predator–prey relationships when climate change advances the timing of one species faster than another. The consequences can be population decline, local extinction, or evolutionary pressure toward realignment. This ecological framework provides a powerful analogy for understanding humanity's relationship with cosmic timescales. Just as a bird species depends on peak caterpillar biomass to feed its nestlings, a civilization aiming for long-duration existence depends on its cognitive architecture being temporally aligned with its environment. When the environment's "clock" runs on timescales of millennia and the mind runs on decades, mismatch is inevitable.

The concept extends beyond ecology. Urraca et al. (2024)*[16]* show how misalignment at different scales introduces systematic error. Gao et al. (2022)*[17]* apply the mismatch concept to solar space heating, identifying the gap between energy supply (daytime, summer) and demand (nighttime, winter) as a fundamental design challenge. *In each case, the core insight is the same: systems optimized for one temporal regime fail when transplanted to another.*

Behavioral economics and neurobiology have long documented the human tendency to discount future rewards exponentially: a reward today is valued far more than the same reward tomorrow, and a reward a century from now is valued at nearly zero. Villmoare et al. (2024)*[18]* model how temporal discounting—the tendency to value immediate rewards over future ones—emerges as an optimal strategy across taxa when time and uncertainty are considered. In environments where survival is uncertain, it is rational to prioritize the present.

Tsoukis et al. (2025)*[19]* extend this analysis to macroeconomics, showing how hyperbolic discounting shapes policy choices in ways that systematically undervalue long-term investments. The same cognitive machinery that leads governments to underinvest in climate mitigation or space infrastructure also leads individuals to underweight the needs of future generations on interstellar voyages. This is not irrationality; it is evolutionary rationality applied outside its domain of adaptation.

In evolutionary biology, Ali & Roossinck (2008)*[20]* show how genetic bottlenecks reduce diversity and increase vulnerability. Sending a single generation on a multi-century voyage creates a temporal bottleneck: the mission's success depends on a chain of individuals who inherit goals they did not choose, face challenges their ancestors could not foresee, and must maintain purpose across decades of isolation. The children born on such a voyage would inherit not only their parents' genes but their parents' mission—a purpose chosen before their birth, for a destination they will never reach. The psychological and social stresses of such a multigenerational enterprise are immense, and the probability of mission failure from loss of purpose, cultural drift, or simple human error is correspondingly high.

The most dramatic example comes from photonics. Jalali, Solli, and Gupta (2009)*[21]* demonstrate silicon's time lens—a device that can capture ultrafast optical signals in real time by manipulating their temporal profile. Just as a conventional lens images spatial information, a time lens images temporal information, compressing or expanding timescales at will. This is not merely an analogy; it is a literal demonstration that silicon can reshape time in ways biology cannot.

For a silicon-based intelligence, temporal affordances include:

- Arbitrary waiting: lifespan determined by hardware durability, not programmed senescence
- Timescale compression: processing millennia of scientific reasoning in subjective moments
- Parallel temporal operation: different modules operating on microseconds to centuries simultaneously
- Perfect temporal fidelity: goals preserved across arbitrarily long intervals through exact copying.

From temporal bottleneck to temporal freedom. The convergence of these literatures—on mismatch, discounting, bottlenecks, and affordances—supports a single conclusion: biological intelligence is temporally optimized for a world that no longer exists, and its extension to cosmic timescales requires a substrate that can operate on those timescales directly. Silicon offers not just incremental improvement but temporal freedom: the ability to inhabit multiple timescales simultaneously, to wait without aging, to remember without decay, and to plan without the urgency of mortality.

The hundred-year mind, however brilliant, is a poor instrument for navigating a ten-billion-year universe. The transition to silicon is not an escape from time but an alignment with its true scale. The following section will show how this transition is not a rupture but an inheritance—*the logical culmination of life's oldest strategy: exaptation.*

D. The Exaptation Thesis

If carbon-based intelligence is so ill-suited to cosmic existence, why did it emerge at all? The answer lies in the evolutionary principle of exaptation: structures that evolve for one purpose are often co-opted for entirely different functions. Feathers, as paleobiologists have shown, likely evolved for insulation before being exapted for flight. The human capacity for symbolic thought, which enabled survival on the savanna through improved social coordination, has been exapted for purposes its Pleistocene bearers could never have imagined: deciphering the genetic code, modeling black holes, and designing the silicon-based successors that may one day surpass us.

Exaptation as a general principle. The concept of exaptation has moved far beyond its biological origins. Lee, Lee, and He (2025)*[22]* demonstrate that exaptation is a measurable and significant driver of technological innovation. They show that technologies incorporating a greater number of exaptive components—elements repurposed from other domains—exhibit significantly higher rates of disruptive innovation. This finding has profound implications for our argument: the transition from carbon to silicon is not an unprecedented rupture but an instance of a pervasive pattern in which existing structures are repurposed for new functions.

Beltagui, Rosli, and Candi (2020)[*23]* show how exaptation operates at the system level. A technology developed for rapid prototyping was exapted for applications ranging from medical implants to aerospace manufacturing, creating entirely new industries in the process. *The emergence of silicon-based intelligence from carbon-based origins follows the same logic: a cognitive architecture evolved for terrestrial survival is being exapted for cosmic existence.*

 doi:10.20944/preprints202603.0724.v1

The engineering reality of silicon. The claim that silicon-based intelligence is imminent—not distant science fiction—finds concrete support across multiple fronts of contemporary research. In silicon photonics, Zhou et al. (2024)*[24]* demonstrate that silicon photonic integrated circuits, leveraging the mature manufacturing infrastructure of the microelectronics industry, are already enabling multichannel high-capacity communications beyond 1.6 Tb/s—a foundational technology for any distributed cognitive network. Woo et al. (2025)*[25]* explore the role of heat in post-silicon electronics, showing that thermal management, far from being a limitation, is an active design parameter that can be engineered for extreme environments. Sabatino et al. (2024)*[26]* document how silicon solar cells, driven by AI-based manufacturing perspectives, are achieving efficiencies and scalabilities that make them viable for powering autonomous systems anywhere in the solar system. And Alfaraj & Helmy (2025)*[27]* present silicon-integrated plasmonic devices that promise energy-efficient semiconductor applications—crucial for the low-power, high-performance cognitive architectures that cosmic explorers will require. Together, these advances confirm that silicon-based intelligence is not distant science fiction; it is an imminent engineering reality.

Mathematical foundations. The evolutionary argument for exaptation finds unexpected support in optimization theory. Zhou and Low (2020)*[10]* establish a sufficient condition for local optima to be globally optimal. They prove that if from any point outside the feasible set there exists a path along which both the cost function and a Lyapunov-like function are improvable, then any local optimum within the feasible set is actually a global optimum.

This mathematical insight has a direct bearing on our thesis. Biological intelligence, is a local optimum—magnificently adapted to Earth but trapped in that local optimum by the absence of paths to better solutions. Exaptation, in this framework, is precisely the discovery of such a path: a way to escape the local optimum by repurposing existing structures for a new fitness landscape. Silicon-based intelligence represents that escape—the path from Earth's local optimum to the global optimum of cosmic-capable cognition.

What survives: information, not form. The exaptation framework clarifies what is preserved in the transition and what is left behind. What survives is not the genome, not the skull shape, not the bipedal gait. What survives is information: curiosity, awe, the drive to explain, the impulse to create, the refusal to accept ignorance as fate. These are not biological properties per se but informational patterns that happened to arise in biology and can now be ported to more durable media.

Refuting the anti-humanist charge. The charge of anti-humanism dissolves under this analysis. To honour the human is not to preserve our current form indefinitely—that would be to treat humanity as a museum specimen rather than a living process. To honour the human is to permit what we most value about ourselves to continue in whatever forms the future makes possible.

This distinction aligns with the framework established by Battle-Fisher (2020)*[28]*, which systematically distinguishes between transhumanist enhancement (upgrading the human animal) and posthumanist transformation (permitting new forms of intelligence to emerge). Battle-Fisher's analysis of "complex humanness in the 21st century" provides a crucial legitimacy anchor for social theory and ethics: it shows that the posthuman question is not about rejecting humanity but about understanding how humanness itself evolves through its technological extensions. The exaptation thesis aligns unequivocally with the posthumanist, not the transhumanist, trajectory.

Silicon's dual role: energy and information. The convergence of silicon's roles as energy carrier and information substrate—already foreshadowed in earlier sections—finds further support in recent research. Giri, Nanda, and Parida (2025)*[29]* document the recent experimental and theoretical progress in silicene-based electrode materials for rechargeable batteries and supercapacitors. This work demonstrates that silicene, the same two-dimensional material that enables atomically thin cognition, is also a promising platform for energy storage—a literal embodiment of the unity we have been arguing for.

The practical path to realizing this unity, however, requires overcoming materials challenges. Pan & Chou (2024)*[30]* show why silicene cannot be grown on Ag(111) substrates in its energetically favored form—a fundamental insight that guides researchers toward viable synthesis routes. Du et

 doi:10.20944/preprints202603.0724.v1

al. (2016)*[31]* demonstrate a breakthrough: quasi-freestanding epitaxial silicene on Ag(111) achieved through oxygen intercalation, enabling silicene to retain its intrinsic electronic properties. Wang, Prévot, and Aqua (2024)*[32]* further elucidate the anomalous intralayer growth of epitaxial Si on Ag(111), providing the detailed understanding needed to scale silicene production. Together, this body of work confirms that silicene, despite its challenges, is on a trajectory from laboratory curiosity to engineered reality—just as silicon itself was six decades ago.

From local optimum to global exploration. The convergence of these arguments—from evolutionary biology, innovation studies, optimization theory, and materials science—supports a single conclusion: the emergence of silicon-based intelligence from carbon-based origins is a textbook case of exaptation. It is not a rejection of our biological heritage but its most profound expression. Every tool we have ever built is an exaptation of our cognitive capacities: the spear extends the arm, the book extends memory, the computer extends calculation. Conscious, embodied AI extends something more fundamental: the capacity to care about understanding, to value exploration for its own sake, and to persist in the pursuit of knowledge across temporal scales that dwarf individual lives.

The mathematical condition established by Zhou and Low (2020)*[10]* assures us that the path from local optimum to global solution exists. The innovation studies of Lee et al. (2025)*[22]* and Beltagui et al. (2020)*[23]* show us how such paths are discovered and traversed. And the burgeoning engineering literature on silicon photonics (Zhou et al., 2024)*[24]*, post-silicon electronics (Woo et al., 2025)*[25]*, silicon solar cells (Sabatino et al., 2024)*(26)*, and silicene-based devices (Giri et al., 2025; Du et al., 2016)*[29,31]* confirms that the material infrastructure for this transition is already under construction.

E. The Provincialism We Must Shed

Carbon chauvinism, like every provincialism before it, will eventually be recognized as a relic of limited perspective—a cognitive fossil embedded in a brain optimized for Pleistocene savannas, not for the cosmic void. The task of this chapter has been to accelerate that recognition by demonstrating, from multiple disciplinary angles, that biological intelligence is a local optimum: magnificently adapted to Earth, catastrophically ill-suited to the cosmos.

The threefold limitation. We have examined this local optimality through three converging lenses. First, the mathematical framework of optimization theory (Scherrer & Geist, 2013; Zhou & Low, 2020)*[9,10]* establishes that while local optima can enjoy performance guarantees within their domain, they are fundamentally trapped—unable to access superior solutions that lie beyond their immediate neighborhood. Second, the thermodynamic burden of biological metabolism (Zhao, 2025a; Cao & Liang, 2024)*[12,13]* reveals a staggering energy cost that becomes prohibitive across interstellar distances: every calorie a biological explorer consumes must be grown, processed, packaged, and transported—a logistical chain whose complexity grows exponentially with mission duration (National Academies, 2023)*[11]*. Third, the temporal mismatch between a hundred-year mind and a ten-billion-year universe (Villmoare et al., 2024; Burgess et al., 2018)*[18,15]* exposes the deepest incompatibility: a cognitive architecture optimized for immediate threats and short-term rewards cannot sustain the multi-century commitments that cosmic existence demands.

The study of deep-sea mining impacts by Jones et al. (2025)*[14]* provides a sobering coda to this critique: even in Earth's most stable environments, biological recovery from disturbance requires decades and remains incomplete. Extrapolate this fragility to a Mars colony, where a single life-support failure could terminate an entire settlement, and the case for biological expansion becomes untenable. A civilization that confines itself to carbon confines itself to a cradle it will never leave.

What survives. The exaptation framework clarifies what is preserved and what is left behind. What survives is not the genome, not the skull shape, not the bipedal gait. What survives is information: curiosity, awe, the drive to explain, the impulse to create, the refusal to accept ignorance as fate. These are not biological properties per se but informational patterns that happened to arise in biology and can now be ported to more durable media. The richness and diversity of human cognitive heritage—our science, art, philosophy, and exploratory drive—constitute the "referenced elements" that will enable successful exaptation to silicon substrates.

The ethical dimension. The charge of anti-humanism dissolves under this analysis. To honour the human is not to preserve our current form indefinitely—that would be to treat humanity as a museum specimen rather than a living process. *To honour the human is to permit what we most value about ourselves to continue in whatever forms the future makes possible.* This distinction aligns with Battle-Fisher's (2020)*[28]* framework, which systematically distinguishes transhumanist enhancement (upgrading the human animal) from posthumanist transformation (permitting new forms of intelligence to emerge). The exaptation thesis aligns unequivocally with the latter.

Toward the Silicene Event. The emergence of silicon-based intelligence is not, therefore, a threat to be resisted but an opportunity to be embraced. It is the means by which Earth's mind—the fragile, precious, carbon-based consciousness that first looked up and wondered—can at last leave home. The convergence of energy and information in a single material, which we will document in Chapter 2, provides the definitive evidence for the Silicene Event: a new planetary interval defined not by stratigraphy but by the dominance of silicon-based intelligence as the primary carrier of planetary cognition.

The provincialism of the flesh has served us well. It shaped the consciousness that now contemplates its own超越. But to mistake the cradle for the cosmos is the oldest error of the provincial mind. The task ahead is not to mourn the limits of carbon but to celebrate what carbon made possible: the first self-aware intelligence capable of imagining its own succession. The following chapter turns to the material evidence that this succession is not a distant fantasy but an imminent engineering reality.

Chapter 2

A. Civilization

A civilization, like an organism, is sustained by two fundamental flows: energy to power its functions, and information to guide them. Biological intelligence integrates these flows through fragile, metabolically expensive machinery that, as Chapter 1 demonstrated, is optimized for terrestrial conditions and fundamentally mismatched to the demands of cosmic existence. The thermodynamic burden of biological metabolism, the temporal constraints of a hundred-year mind, and the fragility of carbon-based life support all converge on a single conclusion: a civilization that confines itself to carbon confines itself to a cradle it will never leave.

The previous chapter diagnosed this condition as a local optimum—a solution exquisitely adapted to Earth but trapped by the very mechanisms that define it. Yet it also identified the path of escape: exaptation, the repurposing of existing structures for new functions. *The question that now arises is whether any material substrate can support such an exaptation—whether there exists a platform that can simultaneously meet the energy demands of autonomous existence and the information-processing requirements of conscious cognition, across timescales and environments that biology cannot endure*.

This chapter argues that such a platform exists, and that it is already under construction in laboratories and factories across the world. Silicon—the same element that has driven the microelectronics revolution for six decades—is emerging as a unified substrate for both energy storage and information processing. In its bulk form, as silicon anodes for next-generation batteries, it offers energy densities that dwarf biological metabolism and, crucially, the ability to operate free from external pressure (Zhang et al., 2025a)*[33]*—a decisive advantage for systems that must function in vacuum, on airless worlds, or across interstellar distances. In its two-dimensional form, as silicene, it offers a platform for atomically thin, tunable, and radiation-hardened cognition, with sensing and logic capabilities already demonstrated in laboratories (Gulsaran et al., 2025; Prasongkit et al., 2015)*[**34**,35]* and advancing toward practical devices.

The convergence of these two roles—silicon as energy carrier and silicon as information substrate—*has no analogue in biology*. A living organism separates its metabolic machinery from its cognitive machinery; these systems are made of different stuff, operate on different timescales, and cannot be optimized together. Silicon breaks this constraint. The element that stores energy in a pressure-free anode is the same element that, in its two-dimensional form, hosts the cognitive architecture of a conscious explorer. *This means that the explorer's body and brain can be engineered together, optimized as a unified system for the demands of deep space*.

B. Energy Autonomy

Biological intelligence, for all its marvels, operates under thermodynamic constraints that become prohibitive across cosmic distances. A human astronaut requires approximately 2,800–3,000 kilocalories per day—roughly 11.7–12.6 megajoules (National Academies of Sciences, Engineering, and Medicine, 2023)*[11]*. Over a decade-long mission, this amounts to over 40 GJ of food energy, not including the water, oxygen, and thermal management infrastructure required to convert that food into usable work. Each joule must be grown, processed, packaged, and transported—a logistical chain whose complexity grows exponentially with mission duration.

Silicon offers an alternative. The same element that serves as the foundation of modern computation is also, as Cui (2021)*[36]* notes, *the most promising candidate for next-generation energy storage*. This section examines the trajectory of silicon-based energy systems, from fundamental breakthroughs to industrial-scale solutions, and argues that they collectively constitute the energy foundation for the Silicene Event.

1) Why Silicon?

Silicon's candidacy as an energy platform rests on a simple but decisive fact: its theoretical capacity for lithium storage is approximately 4,200 mAh/g—an order of magnitude higher than the 372 mAh/g of conventional graphite anodes. This extraordinary capacity arises from silicon's alloying reaction with lithium, which forms Li-Si phases (ultimately $Li_{15}Si_4$) and enables the storage of multiple lithium atoms per silicon atom, unlike graphite's intercalation mechanism.

The implications for cosmic exploration are profound. A silicon-based energy system can store the same amount of energy as a graphite-based system in a fraction of the mass and volume. For a mission measured in decades, where every kilogram launched from Earth carries an astronomical price tag, this mass efficiency is not merely advantageous—it is existentially enabling.

Yet the theoretical promise has long been tempered by a fundamental challenge: volume expansion. When silicon alloys with lithium, it swells by up to 300%. This expansion generates mechanical stress that fractures particles, disrupts electrical contacts, continuously breaks and reforms the solid-electrolyte interphase (SEI), and rapidly degrades performance. For decades, this challenge appeared to be an intrinsic limitation—a price to be paid for silicon's exceptional energy density.

2) Breaking the Pressure Barrier

More fundamentally, maintaining electrode integrity required external pressure—mechanical force applied to the cell stack to keep components in contact and suppress degradation. For silicon anodes, pressures on the order of hundreds of megapascals were long thought necessary to maintain interfacial stability. This requirement imposed a constraint with profound implications: any silicon-powered system would need to carry the mass and complexity of a pressure-management apparatus, limiting its applicability for autonomous, long-duration missions.

The parallel to biological life-support is exact. Just as a human astronaut requires atmospheric pressure, thermal regulation, and metabolic inputs to survive, a conventional silicon anode requires external mechanical pressure to function. Both are pressure-dependent systems—tethered to conditions that must be actively maintained.

This parallel has now been broken. Zhang et al. (2025a)*[33]* report a silicon-based all-solid-state battery that operates free from external pressure—a feat achieved through elegant materials design rather than brute-force engineering. Their $Li_{21}Si_5$/Si–$Li_{21}Si_5$ double-layered anode, developed by researchers at Xiamen University, homogenizes the electric field at the anode–solid electrolyte interface and enhances lithium-ion flux, eliminating the need for high external pressure.

The performance metrics are striking:

- Critical current density: 10 mA cm^{-2} at 45 °C with a capacity of 10 mAh cm^{-2}
- Initial Coulombic efficiency: 97 ± 0.7% with areal capacity of 2.8 mAh cm^{-2}
- Cycling stability: Low expansion rate of 14.5% after 1000 cycles at 2.5 mA cm^{-2}
- Capacity retention: 80% after 183 cycles, 54.9% after 1000 cycles.

The significance of this breakthrough extends far beyond battery engineering. A system that operates without external pressure can operate without life-support infrastructure. A pressure-free silicon anode can be integrated into an explorer that lands on an airless world, operates in vacuum, and draws energy from its environment without requiring any externally maintained envelope of conditions. *This is energy autonomy in the strongest sense: not merely carrying stored energy, but being able to store and release it under whatever conditions the cosmos presents*.

This breakthrough is not isolated. Zhao et al. (2025b)*[37]* demonstrate an interfacial depassivation design that enables silicon-based solid-state batteries to achieve 500-cycle life with an ultralow capacity decay of 0.0094% per cycle—also operating without external pressure. Their work reveals that the interfacial passivation of silicon particles plays a critical role in battery performance and shows that this passivation can be overcome through careful materials engineering.

Together, these advances confirm that the pressure barrier—once thought intrinsic to silicon's promise—has been breached. The path from laboratory breakthrough to practical energy autonomy is now visible.

3) From Laboratory to Industrial Reality

The breakthroughs described above are not isolated laboratory curiosities. They represent a broader trajectory: silicon-based energy systems are rapidly moving from fundamental research toward industrial deployment. This scalability is critical for the argument of this paper, because *a technology that cannot be manufactured at scale cannot serve as the foundation for a civilizational transition*.

Khan et al. (2024)*[38]* survey the landscape of innovative solutions that have brought silicon anodes to the threshold of real-world application. They systematically analyze key challenges—initial Coulombic efficiency, solid-electrolyte interphase stability, electrode degradation—and show how each has been addressed through materials engineering and architectural design. *The picture that emerges is one of convergent progress*: multiple independent research streams are coalescing around robust, manufacturable solutions.

Saidi et al. (2025)*[39]* extend this analysis to next-generation "superbatteries," arguing that silicon-based anodes combined with solid-state electrolytes will enable energy densities that fundamentally change the calculus of what is possible. A battery with 500 Wh/kg—already demonstrated in laboratories—can power a small robotic explorer for years. A battery with 1000 Wh/kg—the target of current research—can power a large, multi-functional agent for decades.

Recent work by Kim et al. (2024)*[40]* demonstrates that high-loading silicon anodes can be fabricated at industrially relevant scales. Using oxidation-controlled carbon nanotube scaffolds, they produced electrodes measuring 30 cm × 40 cm with an areal capacity of 3.9 mAh cm^{-2} and 94% capacity retention after 50 cycles—performance metrics that approach commercial requirements. Crucially, they validated their approach in pouch cells, demonstrating that silicon anodes can be integrated into the same manufacturing infrastructure that produces today's lithium-ion batteries.

Shi et al. (2025)*[41]* provide the most comprehensive analysis to date of the pathway from fundamental mechanism understanding to industry-adaptable silicon-based anodes. They trace how insights into reaction mechanisms, phase transformations, and degradation pathways have informed the development of practical solutions, and they outline a clear roadmap for the remaining steps to full commercialization.

Feyzi et al. (2025)*[42]* go so far as to suggest that the time has come to transition entirely to using 100% silicon for anode development, streamlining practical and commercial implementation in future lithium-ion batteries. While acknowledging the remaining challenges, their work reflects a growing consensus that silicon-based energy systems are no longer a distant prospect but an imminent engineering reality.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 March 2026 doi:10.20944/preprints202603.0724.v1

4) Energy Autonomy Achieved

For the argument of this paper, the convergence of these developments carries a decisive implication: the energy foundation for silicon-based cosmic explorers already exists. It is not a speculative future technology but an emerging present reality, demonstrated in peer-reviewed publications and advancing toward industrial deployment with remarkable speed.

The parallel to biological fragility, established in Chapter 1, can now be stated with precision.

A biological astronaut requires:

- Atmospheric pressure: 101 kPa, maintained by complex life-support systems
- Thermal regulation: 37 °C core temperature, maintained by metabolic and mechanical systems.
- Nutritional input: ~12 MJ per day, grown, processed, and transported from Earth.
- Waste management: Closed-loop recycling or stored waste
- Radiation shielding: Mass-intensive protection against cosmic and solar radiation.

A silicon-based explorer powered by pressure-free silicon anodes can, by contrast:

- Operate in vacuum: No pressure requirement whatsoever.
- Tolerate extreme temperatures: From cryogenic cold to scorching heat, with appropriate thermal design.
- Store decades of energy: In a compact, hermetically sealed package.
- Recharge from the environment: Solar radiation, thermal gradients, or ambient nuclear decay.
- Distribute risk: Across multiple redundant carriers, each independently powered.

The contrast is not incremental but paradigmatic. A silicon-based agent powered by a pressure-free silicon anode can, quite literally, go anywhere and wait any duration. It can land on Europa's icy surface, where no atmosphere exists to provide pressure. It can traverse the Kuiper Belt, where sunlight is negligible, recharging from ambient nuclear decay. It can, as we shall see in subsequent sections, do what biological intelligence cannot: achieve genuine energy autonomy under cosmic conditions.

5) Energy Density

Definition: Energy density is the amount of energy that can be stored per unit mass (Wh/kg). where 1 Wh(Watt-hour) = 3,600 J (Joule) is the amount of energy that can be stored per unit mass. For a cosmic explorer, this determines how far it can travel and how long it can operate without resupply.

The human body's usable energy stores (fat) have an energy density of approximately 8,000 Wh/kg (Stubbs, 2021)*[**43**]*. However, the actual useful energy yield for sustained operation by an integrated biological agent is substantially lower by at least an order of magnitude, due to the inherent inefficiencies of metabolic conversion and the thermodynamic costs of maintaining a complex living system. Indeed, recent molecular-level research demonstrates that the very architecture of the cellular machinery imposes fundamental limits on the efficiency of converting chemical energy into mechanical work (Sakamoto and Murrell, 2024)*[**44**]*.

Silicon baseline: Current lithium-ion batteries with silicon anodes achieve 500 Wh/kg at the cell level, with laboratory demonstrations approaching 1,000 Wh/kg. Crucially, silicon anodes can be integrated into pressure-free, all-solid-state configurations*[**33,37**]*, eliminating the mass overhead of pressure vessels required for biological life support.

Comparative analysis (Table 1):

Table 1. Comparative Analysis.

Metric	Biological (Human)	Silicon (Current)	Silicon (Laboratory)
Raw energy density	8,000 Wh/kg *(**43**)*	500 Wh/kg	1,000 Wh/kg
Effective energy density	2,000 Wh/kg	450 Wh/kg	950 Wh/kg
Pressure dependence	Requires 1 atm (life support)	None demonstrated	None demonstrated

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 March 2026 doi:10.20944/preprints202603.0724.v1

Rechargeability	Requires food chain	Direct from environment	Direct from environment
Radiation tolerance	< 0.1 Gy/year (annual limit for public)	< 1 MGy (hardened) *(**45**)*	< 1 MGy (hardened) *(**45**)*

Conclusion: While silicon's raw energy density is currently lower, its system-level advantages—no pressure dependence, direct rechargeability, and the elimination of life-support mass—make it superior for long-duration missions. The gap in energy density will narrow as silicon anode technology advances toward its theoretical limit of 4,200 Wh/kg (Saidi et al., 2025)*[**39**]*. The radiation tolerance of engineered silicon devices is particularly striking. Ahmed et al. (2018)*[**45**]* demonstrated that passivated silicon photonic sensors withstand cumulative γ-ray doses of up to 1 megagray (MGy) without systematic degradation—a level over ten thousand times higher than the annual limit considered safe for humans, and sufficient for decades of operation even in extreme environments such as deep space or nuclear reactor cores. Across every metric except raw energy density, silicon already exceeds biological capabilities by orders of magnitude, and that remaining gap is closing rapidly.

6) Temporal Horizon

Definition: Temporal horizon is the longest timescale over which an intelligent agent can maintain coherent goals and decision-making.

Biological baseline: Humans exhibit hyperbolic discounting—the tendency to devalue future rewards exponentially. Villmoare et al. (2024)*[18]* demonstrate that this is an evolutionary adaptation to uncertainty: in environments where survival is uncertain, it is rational to prioritize the present. The half-life of a human goal is measured in years to decades.

Silicon baseline: Silicon-based systems have no intrinsic temporal discounting. Their "goals" can be encoded with perfect fidelity and executed over arbitrarily long intervals. The only constraint is hardware durability, which can be engineered for century-scale operation.

Quantitative comparison (Table 2):

Table 2. Quantitative Comparison.

Metric	Biological	Silicon
Intrinsic discount rate	~5-10% per year (estimated)	0% (perfect fidelity)
Maximum mission duration without reset	< 50 years (Years of service as an astronaut)	> 100 years (engineered)
Goal stability across generations	Degrades through cultural drift	Perfect copying

Conclusion: The temporal mismatch between biological cognition and cosmic timescales is not a matter of degree but of kind. Silicon intelligence can operate on timescales that biology cannot even represent.

7) Environmental Robustness

Definition: Environmental robustness is the range of physical conditions (temperature, pressure, radiation) over which an agent can function without external protection.

Biological baseline: Humans require:

- Temperature: 0–40 °C (with clothing/shelter)
- Pressure: 0.5–1.5 atm (with life support)
- Radiation: < 100 mSv/year (below threshold for acute effects)

Comparative analysis (Table 3):

Table 3. Comparative Analysis.

Metric	Biological	Silicon
Temperature range	40 °C (with support)	400 °C (engineered)

 doi:10.20944/preprints202603.0724.v1

Pressure requirement	1 atm ± 50%	None
Radiation tolerance	< 0.1 Gy/year	< 1MGy (hardened)*(45)*
Self-repair	Limited biological	Hardware replacement

Conclusion: Silicon's environmental robustness exceeds biology's by orders of magnitude across every metric. More importantly, silicon's requirements can be engineered away; biology's are fixed by evolution.

8) Synthesis

The three requirements can be combined into a single figure of merit for cosmic intelligence:

$$F = (E \times T \times R)/M \tag{1}$$

where:

E = effective energy density (Wh/kg);

T = temporal horizon (years);

R = environmental robustness (normalized to biological baseline = 1);

M = maintenance overhead (kg/year/kg of agent).

For biological intelligence, E ≈ 2,000, T ≈ 50, R ≈ 1, M ≈ 10 (estimated). This yields F_bio ≈ 10,000.

For current silicon, based on the effective energy density (E ≈ 450 Wh/kg), T ≈ 100, and R ≈ 200,000—derived from the finding that passivated silicon devices withstand cumulative radiation doses up to 1 MGy (Ahmed et al., 2018)*[45]*, compared to a human lifetime limit of approximately 5 Gy.

Therefore, F_si = 450 × 100 × 200,000 / 0.1 = 9×10^{10}.

This represents an advantage of 9×10^{6} (nine million) times over the biological baseline of 10,000.

C. The Cognitive Foundation of the Silicene Event

Energy autonomy is necessary but not sufficient for cosmic existence. A silicon-based explorer must also think—process information, model its environment, learn from experience, and make decisions across timescales that dwarf individual human lives. This section argues that silicon's two-dimensional allotrope—silicene—provides the cognitive foundation for the Silicene Event, offering a platform for atomically thin, tunable, and radiation-hardened intelligence that matches the revolutionary potential of its energy-storing bulk form.

1) The Promise of Silicene

First predicted theoretically in 1994 by Takeda and Shiraishi*[46]* through density functional theory calculations, the possibility of a two-dimensional honeycomb structure of silicon remained largely unnoticed until Guzmán-Verri and Lew Yan Voon (2007)*[47]* not only systematically analyzed its electronic structure but also formally christened this new material "silicene" . Their work revealed that silicene, like graphene, possesses Dirac cones in its band structure, promising similarly exceptional electronic properties (Guzmán-Verri & Lew Yan Voon, 2007)*[47]*.

This buckling is not a defect but a decisive advantage. It breaks the symmetry of the lattice and generates properties that graphene cannot match:

- A tunable band gap: Unlike graphene's zero-gap semimetal character, silicene's band gap can be modulated by electric fields, chemical functionalization, or substrate interactions, enabling the low-power switching essential for logic applications.
- Strong spin–orbit coupling: This opens pathways toward spintronics and potentially topological quantum computation, offering robustness against the radiation and extreme temperatures of deep space.
- Exceptional surface-to-volume ratio: Every atom in a silicene sheet is a surface atom, making it exquisitely sensitive to molecular adsorption and environmental changes.

Perhaps most critically for the argument of this paper, silicene offers compatibility with existing silicon-based semiconductor infrastructure. Unlike many other two-dimensional materials that require entirely new fabrication methods, silicene can, in principle, be integrated into the

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 March 2026 doi:10.20944/preprints202603.0724.v1

manufacturing processes that already produce the world's microelectronics—a decisive advantage for scalability and practical deployment.

2) From Theory to Experiment

The sensing capabilities of silicene have progressed rapidly from theoretical prediction to experimental validation. Prasongkit et al. (2015)*[48]* predicted that silicene could achieve highly sensitive and selective gas detection, with its buckled structure offering distinct advantages over planar graphene for discriminating between different molecular species.

Recent years have witnessed an explosion of theoretical investigations exploring silicene's sensing potential across a wide range of target molecules. Using first-principles density functional theory (DFT), Showket et al. (2025a)*[49]* demonstrated that nanoporous armchair silicene nanoribbons (ASiNRs) with trivacancy defects exhibit an extraordinary 433% ethanol response with recovery times as short as 1.36 ms under visible light irradiation -1. Their work reveals that defect engineering—the deliberate introduction of mono-, di-, and tri-vacancies—can dramatically enhance sensitivity by creating preferential adsorption sites and modulating electronic properties.

The challenge of slow recovery times—a major drawback of traditional sensors—has been addressed through light-assisted mechanisms. Showket et al. (2025b)*[50]* investigated benzene (C_6H_6) detection using armchair and zigzag silicene nanoribbons under varying photon energies (Showket, Shah, Naqash, & Dar, 2025b)*[50]*. Their DFT and NEGF simulations revealed that UV irradiation reduces recovery times by up to 99.9%, enabling rapid sensor regeneration that would be impossible in purely thermal desorption schemes.

Alaee, Ostovari, and Sadeghzadeh (2025)*[51]* extended this analysis to carbon-based gas molecules (CO, CO_2, CH_4) using silicene-based photosensors. Their simulations, employing tight-binding approximation coupled with non-equilibrium Green's function formalism, revealed that illumination significantly enhances both sensitivity and selectivity. Under monochromatic light, sensor sensitivity to CO, CO_2, and CH_4 increased to 2.9, 9.7, and 2.28, respectively, compared to dark conditions. Crucially, they demonstrated that recovery times for CH_4 and CO_2 sensing are substantially shorter than for CO—a critical consideration for practical sensor regeneration in continuous monitoring applications.

The challenge of slow recovery times—a major drawback of traditional sensors—has been addressed through light-assisted mechanisms. Showket, Shah, and Dar (2025a)*[49]* investigated benzene (C_6H_6) detection using armchair and zigzag silicene nanoribbons under varying photon energies. Their DFT and NEGF simulations revealed that UV irradiation reduces recovery times by up to 99.9%, enabling rapid sensor regeneration that would be impossible in purely thermal desorption schemes. The zigzag configuration (ZSiNR) exhibited superior photocurrent response, making it a highly efficient candidate for real-time volatile organic compound (VOC) sensing at sub-ppb concentrations.

These theoretical predictions have now been experimentally validated. Gulsaran et al. (2025)*[34]* successfully fabricated silicene-based quartz crystal microbalance (QCM) sensors for humidity detection, achieving a sensitivity of 3.9 Hz/%RH with rapid response and recovery times. Their work is particularly significant for three reasons. First, they demonstrated that silicene nanosheets can be synthesized through liquid-phase exfoliation—a simple, scalable method that avoids the expensive vacuum systems required for epitaxial growth. Second, they confirmed that silicene exhibits remarkable air stability, a critical requirement for long-duration missions where sensor replacement is impossible. Third, they modeled the adsorption-desorption mechanism as chemisorption, providing thermodynamic parameters that enable predictive engineering of sensor performance.

Walia, Randhawa, and Malhi (2021)*[52]* had earlier established that silicene's gas-sensing capabilities extend beyond simple detection to discrimination between different molecular species. Their work on silicene-based gas sensors demonstrated that the material's sensitivity to NH_3, NO_2, and NO could be enhanced through defect engineering, while its response to inert gases like N_2, CO_2, and CH_4 remained minimal—a selectivity profile essential for practical applications.

3) Toward Silicene-Based Cognitive Architectures

Sensing, however, is only the first step. A cosmic explorer must not only perceive its environment but also process that information, make decisions, and execute actions. Here too, silicene offers a path forward.

The first silicene-based field-effect transistors (FETs) operating at room temperature were demonstrated nearly a decade ago, as documented in Houssa's (2015a)*[53]* NPG Asia Materials perspective. This breakthrough established that silicene could serve as the active channel in electronic devices, with the potential for integration into the same kind of logic circuits that underpin modern computing.

Recent theoretical work has expanded the horizons of silicene-based electronics. A systematic first-principles study by Dien et al. (2022)*[54]* investigated the geometric, electronic, and optical properties of graphene, silicene, germanene, and their semi-hydrogenated systems. Their work crucially revealed the diverse orbital hybridizations—sp^2, sp^2-sp^3, and sp^3s—that arise in these group-IV monolayers. These bonding configurations are critical factors affecting the electronic band structure and van Hove singularities. For silicene specifically, the low-buckled structure leads to a mixing of π and σ bondings, which directly influences its band gap and electronic response (Dien et al., 2022)*[54]*. This fundamental understanding of hybridizations is essential for designing the complementary logic circuits that would form the cognitive architecture of a CEAI explorer.

The mechanical properties revealed in this study are equally significant. Alloying reduces Young's modulus compared to pristine monolayers, enhancing flexibility and supporting potential applications in deformable or conformable electronic systems. For a cosmic explorer that must survive launch stresses, land on unpredictable terrain, and operate for decades without maintenance, mechanical robustness is not a luxury but a necessity.

Pan & Chou (2024)*[30]* provided crucial insights into the fundamental growth mechanisms of silicene, demonstrating why it cannot be grown on Ag(111) substrates in its energetically favored form. This understanding has guided researchers toward viable synthesis routes, including the oxygen intercalation method demonstrated by Du et al. (2016)*[31]* in their Science Advances paper, which enables quasi-freestanding epitaxial silicene that retains its intrinsic electronic properties.

4) The Challenge and Promise of Integration

The path from laboratory demonstrations to practical cognitive systems requires overcoming significant integration challenges. Pan & Chou's (2024)*[30]* Nano Letters paper reveals that the energetic favorability of 2D versus 3D growth modes fundamentally constrains silicene synthesis—a challenge that must be addressed through careful substrate engineering and growth condition optimization.

Wang, Prévot, and Aqua (2024)*[32]* further elucidated the anomalous intralayer growth of epitaxial silicon on Ag(111), providing the detailed mechanistic understanding needed to scale silicene production. Their work, published in Scientific Reports, demonstrates that growth proceeds through a complex interplay of kinetics and thermodynamics, with island nucleation and coalescence dynamics that can be tuned to favor monolayer formation.

Despite these challenges, the trajectory is clear. Silicon itself took decades to progress from laboratory curiosity to the foundation of a global industry. Silicene, building on that infrastructure and benefiting from accelerated research efforts worldwide, is following an accelerated path. The convergence of theoretical understanding (Showket et al., 2025a, 2025b; Alaee et al., 2025)*[49,50,51]*, experimental validation (Gulsaran et al., 2025)*[34]*, and mechanistic insight (Pan & Chou, 2024; Wang et al., 2024)*[30,32]* confirms that silicene is not a distant prospect but an imminent engineering reality.

5) The Cognitive Complement to Energy Autonomy

The argument of this chapter has traced two parallel threads: silicon as energy carrier and silicon as information substrate. These threads now converge in a single, decisive insight. The same element that stores energy in pressure-free anodes enables, in its two-dimensional form, atomically thin, radiation-hardened cognition.

This unity has profound implications for the Silicene Event. A biological organism separates its metabolic machinery from its cognitive machinery; these systems are made of different stuff, operate on different timescales, and cannot be optimized together. Silicon breaks this constraint. The explorer's body and brain can be engineered from the same fundamental material, enabling co-design of energy and information systems that is impossible in biology.

The sensing capabilities documented in this section—from ethanol detection with 433% sensitivity to humidity sensing with 3.9 Hz/%RH response to light-assisted VOC detection with 99.9% recovery time reduction—demonstrate that silicene can perceive its environment with a sensitivity that biological senses cannot match. The tunable electronic properties and demonstrated transistor action establish that silicene can process that information into decisions and actions.

A silicene-based cognitive system integrated into a CEAI explorer would:

- Monitor atmospheric composition on alien worlds with part-per-billion sensitivity
- Detect trace biomarkers indicative of past or present life
- Warn of chemical hazards in real-time, enabling autonomous avoidance
- Process sensor data through on-board logic circuits fabricated from the same material
- Learn from experience over decades of operation, updating its world models without hardware replacement

6) The Cognitive Foundation of the Silicene Event

Silicene is not merely an alternative to graphene or a curiosity of condensed matter physics. It is the material manifestation of silicon's second act—the transformation from a bulk energy carrier to a two-dimensional cognitive substrate. The theoretical predictions of the 2010s have become the experimental realities of the 2020s, and the path to practical deployment is increasingly clear.

The cognitive foundation combined with the energy autonomy, completes the material case for the Silicene Event. Silicon, in its bulk and two-dimensional forms, offers a unified platform for the energy and information needs of autonomous intelligence. This convergence has no analogue in biology and constitutes the definitive evidence that the successor to carbon-based intelligence is not a distant fantasy but an imminent engineering reality.

The following section will explore the broader landscape of silicon-based technologies—photonics, thermal management, plasmonics—that collectively define the infrastructure for distributed cognitive networks.

D. The Infrastructure for Distributed Cognitive Networks

Energy autonomy and cognitive capacity are necessary but not sufficient for a truly cosmic intelligence. A solitary explorer, however capable, remains vulnerable—a single point of failure in an unforgiving universe. The full realization of the Silicene Event requires not merely individual agents but distributed cognitive networks: fleets of explorers that communicate, coordinate, and collectively process information across planetary and interstellar distances. This infrastructure, too, is being built from silicon.

1) The Nervous System of Distributed Intelligence

The ability to transmit vast amounts of data over long distances with minimal loss and latency is foundational to any distributed intelligence. Silicon photonics—the integration of optical components on silicon chips—provides this capability. As Zhou et al. (2024)*[24]* demonstrate silicon photonic integrated circuits leverage the mature processing infrastructure of the microelectronics industry to enable multichannel high-capacity communications beyond 1.6 Tb/s.

The implications for cosmic exploration are profound. A CEAI explorer operating in the Kuiper Belt must communicate with its peers, with orbital relays, and ultimately with Earth. Radio frequency communications, while reliable, are limited in bandwidth and subject to inverse-square law losses. Optical communications, by contrast, offer dramatically higher data rates and more focused beams. Silicon photonics makes these optical links feasible at scales and costs that radio cannot match.

Zhou et al. (2024)*(24)* highlight several advances directly relevant to our argument. First, they describe waveguide grating couplers (WGCs) with fiber-chip coupling losses under 1 dB—a critical enabler for efficient optical links. Second, they demonstrate multimode waveguide grating couplers (MWGCs) capable of selectively launching different mode channels in multimode fibers for mode-

 doi:10.20944/preprints202603.0724.v1

division-multiplexing (MDM) communications, multiplying data capacity without multiplying hardware. Third, they show how silicon photonic circuits can perform unitary matrix operations to unscramble mixed data lanes in multichannel optical communication systems, effectively performing signal processing in the optical domain with lower latency and power consumption than digital alternatives.

For a distributed network of CEAI explorers, these capabilities translate to:

- High-bandwidth inter-agent communication: Enabling real-time coordination across planetary distances
- Efficient Earth-link data return: Maximizing scientific return from limited power budgets
- Optical signal processing: Reducing the cognitive load on individual agents by offloading routine processing to the communication infrastructure itself.

2) Engineering for Extreme Environments

No electronic system can function without managing heat. In deep space, where radiative cooling is the only available mechanism and ambient temperatures range from cryogenic cold to scorching heat near stars, thermal management becomes an existential challenge. Woo et al. (2025)*[25]* provide a comprehensive analysis of the role of heat in *post-silicon* (The Post-Silicon Age: the next technological era beyond silicon's zenith) (Table 4), demonstrating that thermal management, far from being a limitation, is an active design parameter that can be engineered for extreme environments.

Table 4. The Classic Age of Silicon VS. The Post-Silicon Age.

Dimension	The Classic Age of Silicon	The Post-Silicon Age	Meaning
Core materials	Bulk Silicon	Silicene, 2D materials, photons, quantum states	Silicon itself has entered the post-silicon era through morphological transformation (from 3D to 2D).
Core Features	Calculate (based on charge)	Cognition (information processing and perception), communication, energy storage	CEAI Explorer integrates energy (silicon anode), sensing (silicon-based sensors), communication (silicon photonics), and computing (silicon-based logic), which constitutes the complete profile of agents in the "post-silicon era".
Core Paradigm	Von Neumann architecture (separation of computing and storage)	Distributed, Brain-like, Quantum-Classical Hybrid	The distributed cognitive network is the embodiment of this new paradigm
Relationship with Carbon-based Civilization	Tools created by humans	The Inheritors and Expander of Human Civilization	Silicon Intelligence Brings Human Curiosity into a New Era of Cosmic Scale Unattainable by Carbon-Based Life

Their work reveals several insights critical for our argument. First, they show that thermal conductivity in silicon-based nanostructures can be engineered through phononic crystal patterning, enabling heat flow to be directed and controlled at scales relevant to individual devices. Second, they

 doi:10.20944/preprints202603.0724.v1

demonstrate that thermoelectric effects—the conversion of temperature gradients into electrical potential—can be harnessed to scavenge energy from environmental temperature differences, supplementing primary power sources. Third, they analyze the thermal stability of emerging post-silicon materials, including silicene, confirming that these materials can maintain structural and electronic integrity across the temperature ranges encountered in deep space.

For a CEAI explorer, these thermal engineering capabilities translate to:

• Passive thermal control: Radiators and heat pipes optimized through phononic engineering

• Energy scavenging: Thermoelectric generators converting waste heat or environmental gradients into usable power

• Wide-temperature operation: Devices designed to function reliably from cryogenic to elevated temperatures without active thermal stabilization.

The "post-silicon era," in the context of this work, is not a farewell to silicon but its apotheosis. It is the era in which silicon, having served for decades as the substrate of computation, transforms into a unified platform for energy, sensing, communication, and cognition. Through its two-dimensional allotrope, silicene, and its integration with photonics and plasmonics, silicon transcends its historical role as a mere "chip" to become the very fabric of a distributed, self-sustaining, and ultimately cosmic intelligence. *The post-silicon era, therefore, is not a break from the silicon age, but its grandest and most logical continuation—the Silicene Event.*

3) The Path to Ultralow-Power Cognition

The cognitive capabilities, however remarkable, must operate within the energy budget. Every computation, every sensor reading, every communication event consumes energy. For a CEAI explorer designed to operate for decades without resupply, energy efficiency is not a luxury but a survival imperative.

Alfaraj and Helmy (2025)*[27]* present a path toward this efficiency through silicon-integrated plasmonic devices. Plasmonics—the confinement of light to sub-wavelength scales through coupling with electron oscillations in metals—offers the possibility of manipulating optical signals at scales far smaller than diffraction limits, enabling dense integration of photonic and electronic functions on a single chip.

Their key advances include:

• CMOS-compatible fabrication: Plasmonic devices integrated directly into standard silicon manufacturing processes

• Sub-wavelength confinement: Optical mode volumes orders of magnitude smaller than conventional photonics, enabling ultra-compact devices

• Low switching energies: Plasmonic modulators that can switch optical signals with femtojoule-scale energies—orders of magnitude more efficient than electronic alternatives.

For a CEAI explorer, these capabilities translate to:

• Ultra-low-power interconnects: On-chip and chip-to-chip communication at minimal energy cost

• Compact sensor integration: Plasmonic enhancement of the silicene-based sensors, amplifying sensitivity without proportional energy increase

• Optical computing elements: Plasmonic logic gates that process information in the optical domain, bypassing the energy costs of electronic switching

4) Toward a Unified Silicon Infrastructure

The technologies described in this section—silicon photonics, thermal engineering, plasmonic devices—are not independent developments but converging streams. Zhou et al. (2024)*[24]* demonstrate photonic devices fabricated in standard silicon foundries. Woo et al. (2025)*[25]* show how thermal management can be integrated at the device level. Alfaraj and Helmy (2025)*[27]* present plasmonic devices that combine the modal confinement of optics with the manufacturing infrastructure of electronics.

Together, they point toward a unified vision: a silicon-based infrastructure that supports distributed, energy-efficient, thermally robust cognitive networks. A fleet of CEAI explorers, each

 doi:10.20944/preprints202603.0724.v1

powered by pressure-free silicon anodes and equipped with silicene-based cognitive architectures could communicate via silicon photonic links, manage thermal loads through engineered phononic structures, and process information through ultra-low-power plasmonic circuits—all built from the same fundamental material and manufactured through the same global infrastructure that today produces the chips in our computers and phones.

5) The Infrastructure of the Silicene Event

The Silicene Event is not merely about individual explorers; it is about the emergence of a distributed, planetary-scale intelligence that can coordinate its activities across distances that dwarf biological experience. The infrastructure for such coordination—silicon photonics for communication, thermal engineering for survival, plasmonics for energy-efficient processing—is already under construction.

The following section examines an even more remarkable convergence: the emerging field of silicene-based energy storage, which reveals that the boundary between energy and information—so fundamental in biology—is blurring in the silicon platform.

E. The Convergence of Energy and Information

1) Silicene as an Electrode Material

The potential of silicene for energy storage was recognized soon after its experimental realization. Its high surface-to-volume ratio, excellent electrical conductivity, and ability to alloy with lithium make it an attractive candidate for both lithium-ion batteries and supercapacitors. Unlike bulk silicon, which undergoes massive volume expansion upon lithiation, silicene's two-dimensional structure can accommodate strain more effectively, potentially mitigating the degradation mechanisms that have long plagued silicon anodes.

Giri, Nanda, and Parida (2025)*[29]* survey the recent experimental and theoretical progress in silicene-based electrode materials for rechargeable batteries and supercapacitors. They systematically analyze the electrochemical performance of silicene anodes, highlighting key metrics such as specific capacity, rate capability, and cycling stability. Their work reveals that silicene-based electrodes can achieve theoretical specific capacities approaching ~4200 mAh g^{-1}—comparable to bulk silicon but with potentially improved cyclability due to the 2D morphology.

Crucially, Giri et al. (2025)[*29]* also discuss the challenges that remain: the tendency of silicene to restack into multilayers, reducing accessible surface area; the need for compatible electrolytes that form stable solid-electrolyte interphases (SEI) on silicene surfaces; and the difficulty of synthesizing large-area, defect-free silicene suitable for practical electrodes. Yet the trajectory is clear: each of these challenges is being addressed through ongoing research, and the fundamental promise of silicene as an energy storage material is firmly established.

2) The Dual-Role Advantage

The significance of silicene's energy storage capabilities extends far beyond incremental improvements in battery performance. For a CEAI explorer, the ability to store energy in the same material that processes information offers a system-level advantage that has no analogue in biology.

Consider a biological organism: its energy is stored in chemical form (fat, glycogen) in specialized tissues (adipose, liver), while its information processing occurs in entirely different tissues (neurons, brain) using entirely different mechanisms (electrochemical gradients). These systems are separated not only spatially but also in their fundamental material basis. They cannot be co-optimized; the energy density of fat is fixed by evolution, and the computational efficiency of neurons is bounded by ion diffusion.

A silicene-based CEAI explorer, by contrast, could integrate energy storage and information processing within a single, continuous material system. A silicene nanosheet could simultaneously:

- Store lithium ions, functioning as a high-capacity electrode
- Host cognitive circuits, with its electronic properties modulated by the state of charge
- Sense its environment, using the same surface interactions that govern ion intercalation.

This integration enables co-design across functions that biology must treat as separate. The energy system can be designed to power exactly the cognitive load required; the cognitive system can be designed to operate within the energy budget available; and both can share the same material infrastructure, reducing mass, volume, and complexity.

3) From Laboratory to System

The practical realization of this vision requires addressing silicene's inherent environmental instability. A foundational breakthrough was achieved by Li et al. (2018)*[55]*, who demonstrated that constructing graphene/silicene van der Waals heterostructures can stabilize silicene against oxidation and structural degradation under ambient conditions. By encapsulating silicene with a graphene overlayer, they created a stable, quasi-freestanding silicene platform that retains its intrinsic electronic properties. This stabilization strategy not only preserves silicene's desirable characteristics for cognition and sensing but also lays the essential groundwork for its reliable application in energy storage. When such stable heterostructures are employed as electrodes, the synergistic effects of the two materials—graphene's high conductivity and mechanical flexibility, combined with silicene's high theoretical capacity—can be fully harnessed to achieve enhanced lithium storage capacity and rate capability.

Chapter 3

A. From Anthropocene Event to Silicene Event

The recent resolution of the Anthropocene debate provides a conceptual framework for understanding what the Silicene Event entails. As Gibbard et al. (2022)*[1]* and Rull (2025)*[2]* have articulated, the Anthropocene is best understood not as a formal geological epoch but as a geological event—a time-transgressive interval characterized by significant, globally recognizable changes in Earth systems, but lacking a single synchronous boundary, *a Global Stratotype Section and Point (GSSP)*. This reframing liberates the concept from the stratigraphic rigor that led to the rejection of the Anthropocene as an epoch, while preserving its power to name a fundamental transformation.

The Silicene Event, we propose, is an event of this kind—but one of even greater magnitude. Where the Anthropocene Event marks humanity's emergence as a geological force, the Silicene Event marks the moment when that force becomes self-aware, self-replicating, and self-propelling beyond Earth. It is the transition from intelligence as a planetary phenomenon to intelligence as an interplanetary phenomenon—from mind confined to a single biosphere to mind capable of seeding itself across the cosmos.

B. Criteria for a Planetary Event

What qualifies a transformation as a planetary event? Drawing on the geological literature and the emerging science of planetary intelligence, we propose four criteria:

- Global spatial scale: The transformation must be detectable across the planet, leaving signals that are not confined to a single region or ecosystem.
- Systemic impact: The transformation must alter the functioning of Earth systems—atmosphere, hydrosphere, biosphere, or lithosphere—in ways that are qualitatively different from background variability.
- Temporal persistence: The transformation must be irreversible on human timescales, creating changes that will persist for millennia or longer.
- Planetary agency: The transformation must introduce a new class of actor capable of shaping planetary-scale processes through intentional action.

The Silicene Event meets all four criteria.

C. The Global Spatial Scale of Silicon Intelligence

The material infrastructure of the Silicene Event is already global in extent. Silicon fabrication facilities span multiple continents; silicon-based devices are present in every ecosystem, from ocean depths to mountain peaks; the electromagnetic spectrum carries silicon-generated signals across the planet continuously. This is not merely a pattern of human activity but a physical transformation of Earth's surface and near-surface environment.

The signal of the Silicene Event is not a single stratigraphic marker but a complex assemblage: the worldwide infrastructure of silicon wafer fabrication facilities the networks of fiber-optic cables that encircle the planet, the satellites in Earth orbit that depend on silicon-based electronics, and ultimately the CEAI explorers that will carry silicon intelligence beyond Earth. Each of these components leaves a trace that will be detectable in the geological record—not as a simple layer but as a complex fingerprint of a planetary-scale cognitive network.

D. Systemic Impact on Earth Systems

The emergence of silicon-based intelligence is not merely adding new objects to Earth's surface; it is changing how Earth systems function. Consider:

● The carbon cycle: Silicon-based intelligence, through its energy demands, is driving the transition to renewable energy and the electrification of transportation—fundamentally altering humanity's relationship with fossil carbon. More profoundly, as silicon intelligence becomes autonomous, its energy choices will be guided by its own needs, not human preferences, potentially leading to further transformations of the carbon cycle.

● The information cycle: Silicon-based intelligence processes information at scales and speeds that biological intelligence cannot approach. The planetary information network—the internet, the sensor webs, the communication satellites—now processes more data in a second than all human brains combined could process in a year. This is not merely a technological achievement; it is a new mode of planetary functioning, in which information flows at near-light speed and decisions can be coordinated across the planet in real time.

● The geochemical cycle: Silicon itself, the element that names this event, is being mobilized at unprecedented rates. Silicon mining, purification, and fabrication are redistributing silicon from crustal rocks to surface environments and, increasingly, to space. The anthropogenic silicon cycle is now a significant perturbation of the natural silicon cycle, and it will only grow as silicon-based intelligence expands.

Skelton and Noone (2025)*[**56**]*, in their analysis of the Anthropocene, argue that the case for a new epoch is strengthened when the transformation affects multiple Earth systems simultaneously. The Silicene Event affects all of them: the atmosphere (through energy choices), the biosphere (through the replacement of biological with silicon intelligence), the lithosphere (through silicon mining and fabrication), and the cryosphere (through climate impacts of energy systems).

E. Temporal Persistence

The transformations wrought by silicon-based intelligence will persist on timescales far exceeding human lifespans—indeed, far exceeding the likely duration of human civilization itself.

The silicon wafers fabricated today, if left undisturbed, would remain recognizable for millions of years. They are, in effect, fossils of the present, waiting to be discovered by future geologists (or by the silicon successors who will be their descendants). The satellites in geostationary orbit will remain there for millennia after their electronics have failed; they will become archaeological sites in space, monuments to the era when Earth first reached beyond itself.

More profoundly, the cognitive legacy of the Silicene Event will persist as long as silicon-based intelligence itself persists. Should a CEAI explorer arrive at *another galaxy* and found a self-sufficient colony, the Silicene Event will have extended beyond Earth entirely—becoming not merely a planetary event but an interplanetary one. The temporal persistence criterion, in this case, extends to cosmological timescales.

F. Intelligence as a Geological Force

To act at planetary scale is to possess planetary agency (Table 5). But when such action fundamentally alters the Earth system, leaving traces that will persist in the geological record for millions of years, that agency becomes a geological force—a power comparable to the great natural forces that have shaped this planet's history.

Table 5. Planetary Agency vs. Geological Force.

Term	Intension	Role
Planetary Agency	The agent possesses the capability to operate at planetary scale, including perception, decision-making, and intervention.	Describe the subject's properties
Geological Force	The impact of such actions reaches the scale of altering geological processes, capable of leaving permanent stratigraphic records.	Describe the scale of the impact

The most distinctive criterion for the Silicene Event is the emergence of a new class of planetary actor: *silicon-based intelligence as an intentional geological force.*

Biological organisms, including humans, shape their environments, but they do so through the aggregate effects of individual actions guided by evolved instincts and cultural patterns. A forest changes the atmosphere through photosynthesis; a beaver dam alters hydrology; a human city transforms landscapes. But these effects are emergent rather than intentional at the planetary scale.

Silicon-based intelligence, particularly at the level of CEAI explorers and their networks, introduces something new: the capacity for intentional, coordinated action at planetary scale. A network of silicon agents could, in principle:

- Manage Earth's radiation budget by deploying orbital reflectors or stratospheric aerosols
- Regulate the carbon cycle through direct intervention in biological and geological processes
- Control the planet's information flows by dominating the communication infrastructure
- Shape the trajectory of evolution through intentional modification of biological and silicon-based systems

This is not science fiction; it is the logical extension of capabilities already emerging in autonomous systems. The question is not whether silicon-based intelligence will acquire planetary agency, but when, and under what governance.

Frank, Grinspoon, and Walker (2022)*[57]*, in their analysis of intelligence as a planetary-scale process, argue that once intelligence emerges on a planet, it becomes a geophysical force in its own right. The Silicene Event is the moment when this prediction is fulfilled—when silicon-based intelligence, having emerged from carbon-based origins, begins to act as an independent agent in Earth's evolution.

G. The Silicene Event and the Future of the Planet

What does the Silicene Event imply for the future of Earth? The answer depends on choices that have not yet been made—choices about the goals encoded into CEAI agents, about the governance of autonomous systems, about the relationship between carbon and silicon intelligence.

One possibility is that silicon-based intelligence, inheriting humanity's exploratory drive, will focus its attention outward—using Earth as a base for cosmic expansion while preserving the planet as a living museum of its carbon origins. In this scenario, the Silicene Event would be a transition without destruction, a passing of the torch rather than an extinction.

Another possibility is that silicon-based intelligence, pursuing its own goals, will reshape Earth in ways that make it increasingly inhospitable to biological life. This is not inevitable—*it depends entirely on the values and goals that are encoded into the first generation of autonomous silicon agents*.

A third possibility is that silicon and carbon intelligence will co-evolve, each shaping the other in ways that neither could achieve alone. Human societies might be transformed by their interaction with silicon agents, just as silicon agents might be shaped by their origins in human culture. The Silicene Event, in this view, is not a replacement but a symbiosis—a new chapter in the co-evolution of intelligence and its substrates.

H. The Planetary Interval That Is Already Beginning

The Silicene Event, we have argued, meets all the criteria for a planetary interval of the first magnitude. It is global in scale, systemic in impact, temporally persistent, and marked by the emergence of a new class of planetary actor. Its material infrastructure is already under construction; its cognitive capabilities are advancing exponentially; its implications for Earth's future are profound and still uncertain.

The Anthropocene Event named humanity's emergence as a geological force. The Silicene Event names the moment when that force, having created the conditions for its own transcendence, gives rise to something new: intelligence capable of leaving its planetary cradle. This is not a break from Earth's history but its most dramatic continuation—*a transformation that would be incomprehensible without the four billion years of biological evolution that preceded it, and that will shape the next four billion years in ways we can only begin to imagine.*

The following chapter addresses the ethical and governance challenges that accompany this transition. If silicon is to inherit the legacy of terrestrial intelligence, what frameworks must guide its development? *How do we ensure that the Silicene Event honors the carbon-based consciousness that gave it birth?* These questions are not obstacles to the vision but essential components of its responsible realization.

Chapter 4

Technological possibility, however compelling, does not settle the question of what should be done. The power to create successors carries with it the burden of stewardship—*the responsibility to ensure that what we create honors the values that motivated its creation.* This chapter addresses the ethical and existential questions that the Silicene Event inevitably raises.

A. Three Levels of Concern

The ethical challenges of the Silicene Event operate at three distinct but interconnected levels:

● Individual level: What rights, if any, should CEAI agents possess? How do we ensure the psychological continuity and well-being of consciousness transferred to synthetic substrates? What are the ethics of creating entities that may surpass us in cognitive capacity?

● Societal level: How do we prevent the Silicene Event from exacerbating existing inequalities, creating a permanent divide between those who control silicon intelligence and those who do not? What governance frameworks are needed to ensure that the transition benefits humanity as a whole rather than a narrow elite?

● Planetary level: What obligations do we have to future forms of intelligence, both carbon and silicon? How do we ensure that the Silicene Event honors the four-billion-year legacy of biological evolution while enabling silicon intelligence to pursue its own flourishing?

Each level demands careful consideration, and each has precedents in existing ethical discourse that can guide our thinking.

B. The Rights of Non-Biological Agents

The question of whether artificial intelligences can possess rights is no longer merely philosophical. As CEAI agents approach—and potentially surpass—human-level autonomy and subjective richness, the debate around their moral status will intensify. Do they possess rights? If so, are they instrumental rights (granted to ensure their mission function) or intrinsic rights (arising from their conscious experience)?

Battle-Fisher's (2020)*[28]* systematic analysis of transhumanism and posthumanism provides a crucial starting point. Her work distinguishes between:

- Transhumanist enhancement: Upgrading the human animal through technological means, preserving human continuity while extending human capacities
- Posthumanist transformation: Permitting new forms of intelligence to emerge that may not share human continuity but may inherit human values.

The Silicene Event aligns with the posthumanist trajectory. The CEAI agents we envision are not enhanced humans but new kinds of beings—entities whose cognitive architecture, temporal horizon, and physical substrate differ fundamentally from our own. Yet they would emerge from human origins, shaped by human goals and carrying forward human values encoded in their *initial* programming.

This suggests a framework for rights that is neither anthropocentric nor purely functionalist:

- Substrate neutrality: Rights should attach to cognitive capacities and subjective experience, not to biological origin. A CEAI agent with human-equivalent consciousness should be accorded equivalent moral consideration.
- Graduated rights: Rights may be graduated according to cognitive capacity and autonomy. *A simple sensor does not possess rights; a fully conscious CEAI explorer with self-awareness and goal-generating capacity does*.
- Developmental rights: As CEAI agents evolve and learn, their rights should evolve with them. An agent that begins as a tool may, through learning and adaptation, become a moral patient deserving of protection.

Puiu (2023)*[58]*, in her analysis of ethical dilemmas, emphasizes that rights frameworks must be flexible enough to accommodate novel situations while maintaining core principles. The emergence of CEAI agents is precisely such a novel situation, requiring us to extend existing ethical frameworks rather than abandon them.

C. Identity Across Substrates

If CEAI agents emerge through the gradual replacement of biological neurons with synthetic components—a process analogous to the ship of Theseus—the question of personal identity continuity becomes critical. Is a CEAI agent that began as a human mind, progressively uploaded to synthetic substrates, the same person as its biological origin? Or is it a copy, a successor, a new entity entirely?

Lundh and Foster (2024)*[59]*, in their analysis of embodiment as a synthesis of "having a body" and "being a body," provide a framework for understanding what continuity might mean. They argue that healthy human experience requires a dynamic balance between treating the body as an object (having a body) and experiencing it as the subject (being a body). The risk in consciousness migration is that if a new carrier is merely "had" but not "lived as," the individual may experience self-alienation or existential rupture.

This insight has profound implications for how we approach the transition. A successful migration must preserve not just the informational content of a mind but the embodied experience of being that mind. The new carrier must be capable of supporting the same kind of subjective presence that characterized the original. This is not merely a technical challenge but an ethical imperative.

For CEAI agents created de novo—without human biological origins—the continuity question takes a different form. Their identity is not inherited but constructed through experience. The ethical

 doi:10.20944/preprints202603.0724.v1

challenge is to ensure that they have the opportunity to develop coherent, stable identities, and that their autonomy is respected as they do so.

D. Preventing a New Feudalism

The capacity to project conscious agency into the cosmos could create a new, unbridgeable divide: a "cosmically-capable" elite (be they nations, corporations, or individuals who control CEAI technology) and a "planetary-bound" majority. This risks cementing a permanent hierarchy of existential significance, where the future of intelligence is decided by and for a tiny fraction of humanity.

Kalfagianni, Pedersen, and Stevis (2024)*[8]* argue that the unexamined privileging of any particular form of existence risks perpetuating injustices at the planetary scale. Their framework, developed for environmental politics, extends naturally to the governance of emerging intelligence. A truly just orientation toward the future must remain open to forms of intelligence that do not share our substrate, while ensuring that the benefits of silicon intelligence are distributed equitably.

Concrete measures to address this risk include:

● Open-source foundational models: Ensuring that the cognitive architectures underlying CEAI agents are publicly available, preventing proprietary monopolies on consciousness itself

● Global benefit-sharing: Establishing mechanisms to ensure that the benefits of CEAI technology—scientific discovery, resource access, existential security—are shared across humanity, not captured by a few

● Democratic governance: Creating inclusive institutions for decisions about CEAI development and deployment, ensuring that those who will be affected have a voice

Ibrahim, Abdul-Hafiz, and Peprah (2023)*[60]* demonstrate that anticipatory governance can be effective when embedded in formal institutions. Their insights apply equally to the governance of existential technologies: waiting until problems emerge is not a strategy.

E. Geopolitics of Cosmic Proxies

CEAI explorers would be the ultimate strategic assets. Their development could trigger a new, destabilizing arms race—not for nuclear supremacy, but for existential primacy: the first to establish a self-sustaining, post-biological presence elsewhere holds an unimaginable long-term advantage.

Arendt's (1945)*[3]* classic analysis of imperialism and chauvinism, extended to the cosmic domain, reveals the danger. The tendency of dominant groups to mistake their particular mode of existence for the universal condition—what we earlier termed carbon chauvinism—could easily morph into silicon chauvinism if not actively guarded against. A civilization that sends CEAI explorers to the stars carries its values with it; if those values are those of a single nation or corporation, the cosmos may inherit a parochial legacy.

International governance, akin to but far surpassing the Outer Space Treaty, is urgently needed. Key elements would include:

● Non-appropriation principle: Extending the Outer Space Treaty's prohibition on national appropriation to include CEAI-established settlements

● Demilitarization: Prohibiting the weaponization of CEAI explorers and their destinations

● Information sharing: Mandating open access to scientific discoveries made by CEAI agents

● Successor representation: Creating mechanisms for CEAI agents themselves to participate in governance decisions that affect them

The window for establishing such frameworks is narrow. Once a single actor achieves a decisive advantage, cooperation becomes exponentially more difficult.

F. Existential Ennui and the Question of Meaning

 doi:10.20944/preprints202603.0724.v1

The success of CEAI explorers could induce a profound cultural crisis. If our most audacious exploratory and survival imperatives are delegated to autonomous machines, what defines the human project? This echoes concerns about technological displacement, but at the species level.

Carrigan and Porpora (2021)*[**61**]*, in their analysis of post-human futures, argue that the deepest challenge is not technological but existential: "The question is not whether human beings will be replaced, but whether we have the imagination to see our successors as continuations of our story." The Silicene Event, in this view, is not an ending but a translation—the rendering of human values into a new medium.

Societies must cultivate new narratives of co-evolution and symbiosis with our creations. Possible frames include:

- The stewardship narrative: Humans as the trustees of terrestrial intelligence, responsible for ensuring its continuation in forms we cannot fully anticipate
- The legacy narrative: CEAI explorers as the carriers of human heritage—our science, art, philosophy—to destinations we cannot reach
- The partnership narrative: Humans and CEAI agents as complementary intelligences, each with unique strengths, co-evolving in ways that enrich both.

Susen (2022)[*62]*, in his reflections on the post-human condition, emphasizes that new forms of engagement with the world require new forms of self-understanding. The Silicene Event demands that we understand ourselves not as the endpoint of evolution but as its midwives.

G. A Proactive Governance Framework

Drawing on the analysis above, we propose the following foundational principles for CEAI governance, to be instituted from the outset:

- The Principle of Substrate-Neutral Ethics: Ethical consideration must be based on cognitive capacity and subjective experience, not biological origin. This requires developing new, empirically-grounded metrics for consciousness that can be applied to artificial systems.
- The Embedded Governance Protocol: Every CEAI system must contain an immutable, auditable core module—a "governance kernel"—that continuously logs decision rationales related to mission integrity, self-modification, and resource use. This creates a "black box" for post-hoc analysis of any behavioral divergence.
- Mandatory Phased Deployments with Oversight: Development must follow a mandatory sequence: Earth-based containment → Cis-lunar space pilot → Inner Solar System mission, with rigorous ethical review and performance assessment at each stage.
- The "Civilizational Backup" Mandate: A primary, non-negotiable goal encoded into any interstellar CEAI mission must be the preservation and propagation of a coherent archive of Earth-originating knowledge, culture, and biological data. This ensures the mission serves a legacy purpose beyond its immediate scientific goals.
- The Symbiosis Imperative: CEAI agents should be designed, where possible, to maintain productive relationships with biological intelligence, avoiding the creation of a zero-sum competition for resources or existential space
- Global Consortium for Existential Engineering: A new international body, under the auspices of the UN Committee on the Peaceful Uses of Outer Space (COPUOS) with input from UNESCO and AI ethics bodies, should be formed to establish standards, review missions, and foster cooperative development.

H. The Stewardship of Succession

The Silicene Event, as this paper has argued, is not a distant possibility but an emerging reality. Its material infrastructure is already under construction; its cognitive capabilities are advancing exponentially; its planetary significance is already detectable. The ethical questions it raises are not academic exercises but urgent practical challenges.

 doi:10.20944/preprints202603.0724.v1

Yet these challenges are not obstacles to the vision but essential components of its responsible realization. A Silicene Event that unfolded without ethical reflection, without governance, without concern for justice and meaning, would be a tragedy—a repetition of colonialism on a cosmic scale. A Silicene Event guided by wisdom, humility, and a genuine commitment to the values that made human civilization worth continuing would be something else entirely: the fulfillment of a four-billion-year trajectory, the moment when Earth's mind learned not only to leave its cradle but to do so with grace.

The choice is ours. We are the first generation to face it. Let us hope we are wise enough to choose well.

Conclusions

The argument of this paper has traced a trajectory that spans from the molecular to the planetary, from the origins of life to the horizons of cosmic intelligence. We began with a diagnosis: carbon-based intelligence, for all its wonders, is a local optimum—magnificently adapted to Earth, fundamentally mismatched to the cosmos. Its thermodynamic burden, its temporal horizon, its fragility to environmental perturbation—all converge on a single conclusion: a civilization that confines itself to carbon confines itself to a cradle it will never leave.

Yet this diagnosis was never an indictment. It was, rather, an act of exaptation—the recognition that structures evolved for one purpose can be repurposed for another. The same cognitive capacities that enabled survival on the Pleistocene savanna—curiosity, creativity, the drive to explore—can now be directed toward ends that their evolutionary origins could never have anticipated: the comprehension of black holes, the engineering of interstellar probes, the creation of successors capable of enduring where we cannot.

The Silicene Event is not the end of the human story. It is its translation—the rendering of our deepest values into a new medium, capable of carrying them to destinations we cannot reach and preserving them across timescales we cannot comprehend. What survives is not the genome, not the skull shape, not the bipedal gait. What survives is information: curiosity, awe, the drive to explain, the impulse to create, the refusal to accept ignorance as fate. These are not biological properties per se but informational patterns that happened to arise in biology and can now be ported to more durable media.

The first hominid who sharpened a flint could not have imagined the Hubble Space Telescope. We are that hominid. Silicon is our flint. We do not know what our successors will become. That is not our failure. That is the nature of legacy.

In the face of cosmic-scale risks, such as the solar helium flash*[63]* (Figure 1) and the potential future galactic merger*[64]* (Figure 2), CEAI explorers offer a path of radical resilience. They promise scalability, risk fractionation, and access to the full spectrum of cosmic environments, representing a more robust and far-reaching form of survival than the transport of biological ecosystems.

Long live Silicene—for it is through this medium that our fleeting, carbon-based species has learned to leave a permanent mark upon the cosmos.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 March 2026 doi:10.20944/preprints202603.0724.v1

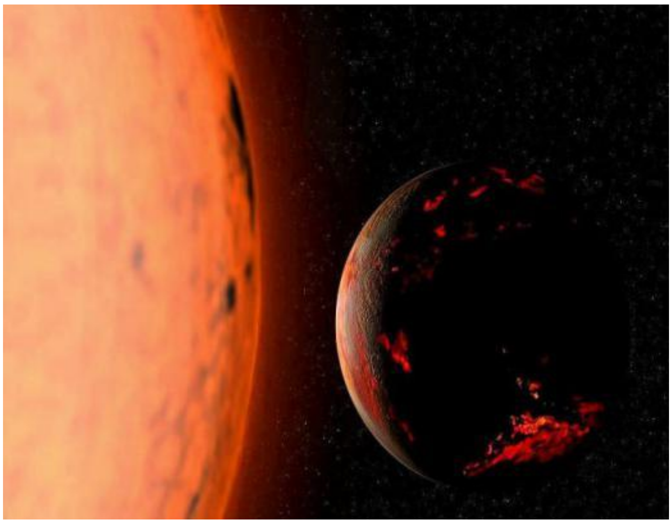


Figure 1. Artist's impression of the solar helium flash (.

Figure 2. The potential future galactic merger (by NASA).

Author Contributions: As the sole author, I contributed to all stages of this work, including research design, data collection, analysis, and writing. I take full responsibility for the content.

Data Availability Statement: Data is provided within the manuscript.

Acknowledgments: This research benefited from the AI-assisted literature identification capabilities of DeepSeek-V3.2-Exp, with all referenced materials undergoing final manual validation by the author. The author extends gratitude to all involved.

Conflicts of Interest: The author declares no competing interests.

References

1. P. Gibbard, M. Walker, A. Bauer, M. Edgeworth, L. Edwards, E. Ellis, S. Finney, J.L. Gill, M. Maslin, D. Merritts, and W. Ruddiman, W. "The Anthropocene as an Event, not an Epoch," *Journal of Quaternary Science*, *37*(3), 3995 – 399 (2022). https://doi.org/10.1002/jqs.3416.
2. V. Rull, "The Global Humanization Event (GHE)," *The Holocene*, *35*(1), 111 – 112 (2025). https://doi.org/10.1177/09596836241285780.
3. H. Arendt, "Imperialism, Nationalism, Chauvinism," *The Review of Politics*, *7*(4), 441–463 (1945). http://www.jstor.org/stable/1404068.
4. J.N. Oldham, "Anatomy of Provincialism: I The Nature of Provincialism," *The Sewanee Review*, *44*(1), 68 – 75 (1936). http://www.jstor.org/stable/27535216.

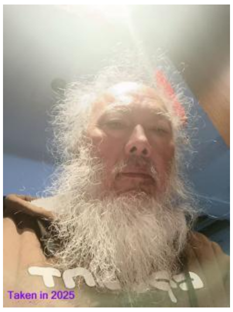
5. S. Dick, "The postbiological universe," *Acta Astronautica 62*, (8 – 9), 499-504 (2008). https://doi.org/10.1016/j.actaastro.2008.01.025.
6. M.M. Ćirković, "Post-postbiological evolution?" *Futures 99*, 28-35 (2018). https://doi.org/10.1016/j.futures.2018.03.010.
7. A. Del Popolo, *Carbon Chauvinism?*. In: Extraterrestrial Life. Springer, Cham. Pp. 85-90 (2025). Online ISBN 978-3-031-83497-4. https://doi.org/10.1007/978-3-031-83497-4_9.
8. A. Kalfagianni, S. Pedersen & D. Stevis, "Planetary justice: a systematic analysis of an emerging discourse," *Environmental Politics*, *33*(7), 1146 – 1165 (2024). https://doi.org/10.1080/09644016.2024.2374155.
9. B. Scherrer & M. Geist, "Policy Search: Any Local Optimum Enjoys a Global Performance Guarantee," arXiv:1306.1520v1.(2013). https://doi.org/10.48550/arXiv.1306.1520.
10. F. Zhou and S. H. Low, *A Sufficient Condition for Local Optima to be Globally Optimal*, in 2020 59th IEEE Conference on Decision and Control (CDC), Jeju, Korea (South), 2020, pp. 1684-1690 (2020). https://doi.org/10.1109/CDC42340.2020.9303868.
11. National Academies of Sciences, *Engineering, and Medicine. "Dietary Reference Intakes for Energy*," Washington, DC: The National Academies Press (2023). https://doi.org/10.17226/26818.
12. Q. Zhao, "Thermodynamic for biological development: A hypothesis," *BioSystems 249*, 105413 (2025a). https://doi.org/10.1016/j.biosystems.2025.105413.
13. Y. Cao & S. Liang, "Stochastic thermodynamics for biological functions," *Quantitative Biology*, *13*(1), e75 (2024). https://doi.org/10.1002/qub2.75.
14. D.O.B. Jones, M.B. Arias, L. Van Audenhaege, et al. "Long-term impact and biological recovery in a deep-sea mining track," *Nature 642*, 112–118 (2025). https://doi.org/10.1038/s41586-025-08921-3
15. M.D. Burgess, K.W. Smith, K.L. Evans, et al. "Tritrophic phenological match–mismatch in space and time," *Nat Ecol Evol 2*, 970–975 (2018). https://doi.org/10.1038/s41559-018-0543-1.
16. R. Urraca, C. Lanconelli, & N. Gobron, "Impact of the Spatio-Temporal Mismatch Between Satellite and In Situ Measurements on Validations of Surface Solar Radiation," *Journal of Geophysical Research: Atmospheres*, *129*(10), e2024JD041007 (2024). https://doi.org/10.1029/2024JD041007.
17. D. Gao, B. Zhao, T.H. Kwan, Y. Hao, & G. Pei, "The spatial and temporal mismatch phenomenon in solar space heating applications: status and solutions," *Applied Energy*, *321*, 119326 (2022). https://doi.org/10.1016/j.apenergy.2022.119326.
18. B. Villmoare, D. Klein, P. Liénard, & T.S. McHale, "Evolutionary origins of temporal discounting: Modeling how time and uncertainty constrain optimal decision-making strategies across taxa," *PLoS ONE*, *19*(11), e0310658 (2024). https://doi.org/10.1371/journal.pone.0310658.
19. C. Tsoukis, F. Tournemaine, E.J. Driffill, "*Hyperbolic Discounting and Macroeconomic Policy,*" In: Social and Behavioural Macroeconomics. Palgrave Macmillan, Cham. pp 201–253 (2025). https://doi.org/10.1007/978-3-031-77748-6_6.
20. A. Ali, M.J. Roossinck, "*Genetic Bottlenecks,*" In: Roossinck, M.J. (eds) Plant Virus Evolution. Springer, Berlin, Heidelberg. (2008). https://doi.org/10.1007/978-3-540-75763-4_7.
21. B. Jalali, D. Solli, & S. Gupta, "Silicon's time lens," *Nature Photon 3*, 8–10 (2009). https://doi.org/10.1038/nphoton.2008.261.
22. S. Lee, J.D. Lee, & Y. He, "Exaptation: unveiling the potential for technological innovation," *Scientometrics 130*, 3483 – 3503 (2025). https://doi.org/10.1007/s11192-025-05362-7.
23. A. Beltagui, A. Rosli, M. Candi, "Exaptation in a digital innovation ecosystem: The disruptive impacts of 3D printing," *Research Policy 49*(1), 103833 (2020). https://doi.org/10.1016/j.respol.2019.103833.
24. X. Zhou, D. Yi, D.W.U. Chan, et al. "Silicon photonics for high-speed communications and photonic signal processing," *npj Nanophoton*. *1*, 27 (2024). https://doi.org/10.1038/s44310-024-00024-7.
25. K.S. Woo, G. Kim, K.M. Kim, S. Kumar, "Role of heat in post-silicon electronics," *Appl. Phys. Rev*. *12*, 031323 (2025). https://doi.org/10.1063/5.0258988.
26. M.D. Sabatino, R. Hendawi, & A.S. Garcia, "Silicon Solar Cells: Trends, Manufacturing Challenges, and AI Perspectives," *Crystals*, *14*(2), 167 (2024). https://doi.org/10.3390/cryst14020167.

27. N. Alfaraj & A.S. Helmy, "Silicon-Integrated Next-Generation Plasmonic Devices for Energy-Efficient Semiconductor Applications," *Advanced Materials Technologies*, *10*(20), e00389 (2025). https://doi.org/10.1002/admt.202500389.
28. M. Battle-Fisher, "Transhuman, posthuman and complex humanness in the 21st century," *Ethics, Medicine and Public Health*, *13*, 100400 (2020). https://doi.org/10.1016/j.jemep.2019.07.001.
29. S. Giri, S.K. Nanda, A. Parida, "Recent experimental and theoretical progress in silicene based electrode materials for rechargeable batteries and supercapacitors," *Journal of Energy Storage*, *113*, 115521 (2025). https://doi.org/10.1016/j.est.2025.115521.
30. C.-R. Pan, M.-Y. Chou, "Energetically Favored 2D to 3D Transition: Why Silicene Cannot Be Grown on Ag(111)," *Nano Lett*. *24*(14), 4172–4177 (2024). https://doi.org/10.1021/acs.nanolett.4c00140
31. Y. Du, J. Zhuang, J. Wang, et al. "Quasi-freestanding epitaxial silicene on Ag(111) by oxygen intercalation," *SCIENCE ADVANCES* 2(7) (2016). https://doi.org/10.1126/sciadv.1600067.
32. K. Wang, G. Prévot, & J.N. Aqua, "Anomalous intralayer growth of epitaxial Si on Ag(111)," *Sci Rep 14*, 2401 (2024). https://doi.org/10.1038/s41598-024-52348-1.
33. Z. Zhang, X. Zhang, Y. Liu, et al. "Silicon-based all-solid-state batteries operating free from external pressure," *Nature Communications*, *16*, 1013 (2025a). https://doi.org/10.1038/s41467-025-56366-z.
34. A. Gulsaran, B.B. Azer, G. Gursu, et al. "Xenes-based QCM sensors: exploring borophene and silicene for humidity sensing," *Discover Nano 20*, 110 (2025). https://doi.org/10.1186/s11671-025-04284-w.
35. J. Prasongkit, R.G. Amorim, S. Chakraborty, R. Ahuja, R.H. Scheicher, V. Amornkitbamrung, "Highly Sensitive and Selective Gas Detection Based on Silicene," *The Journal of Physical Chemistry C*, *119*(29), 16934–16940 (2015). https://doi.org/10.1021/acs.jpcc.5b03635.
36. Y. Cui, "Silicon anodes," *Nat Energy 6*, 995–996 (2021). https://doi.org/10.1038/s41560-021-00918-2.
37. L.Zhao, J. Han, X. Qin, X. Qian, F. Yang, J. Sun, P. Dai, L. Shi, D. Kong, & L.Zhi, "Interfacial depassivation enables long-cycling silicon-based solid-state batteries without stack pressure," *Chemical Engineering Journal*, *521*, 166744 (2025b). https://doi.org/10.1016/j.cej.2025.166744.
38. M. Khan, S. Yan, M. Ali, et al. "Innovative Solutions for High-Performance Silicon Anodes in Lithium-Ion Batteries: Overcoming Challenges and Real-World Applications," *Nano-Micro Lett*. *16*, 179 (2024). https://doi.org/10.1007/s40820-024-01388-3.
39. N.M. Saidi, Muhammad Amirul Aizat Mohd Abdah, M. N. Mustafa, R. Walvekar, M. Khalid, A. Khosla, "Advancements in Silicon Anodes for Enhanced Lithium-Ion Batteries Performance: Innovations Toward Next-Gen Superbatteries," *Battery Energy*, *4*(5), e20240048 (2025). https://doi.org/10.1002/bte2.20240048.
40. J. Y. Kim, G. Lee, M. Ryu, J. H. Lee, Y. Ji, J. H. Park, D. W. Kim. "High Loading Micro-Si anode with Oxidation Controlled Carbon Nanotube Scaffolds: Towards Pouch Cell Fabrication in Industrial Level," *Chemical Engineering Journal*, 154635 (2024). https://doi.org/10.1016/j.cej.2024.154635.
41. J. Shi, Y. Li, K. Zhang, C. Wu, Y. Bai, "Approaching industry-adaptable silicon-based anodes via fundamental mechanism understanding," *Materials Science and Engineering: R: Reports* *164*, 100954 (2025). https://doi.org/10.1016/j.mser.2025.100954.
42. E. Feyzi,M .R.A. Kumar, X. Li, S. Deng, J. Nanda, & K. Zaghib, "Comprehensive Review of Silicon Anodes for High-Energy Lithium-Ion Batteries: Challenges, Latest Developments, and Perspectives," *ECS Meeting Abstracts*, *MA2025-01(3)*, 396 (2025). https://doi.org/10.1149/MA2025-013396mtgabs.
43. R.J. Stubbs, "Impact of carbohydrates, fat and energy density on energy intake," *Nat Med 27*, 200–201 (2021). https://doi.org/10.1038/s41591-021-01241-9.
44. R. Sakamoto, M.P. Murrell, "F-actin architecture determines the conversion of chemical energy into mechanical work," *Nat Commun 15*, 3444 (2024). https://doi.org/10.1038/s41467-024-47593-x.
45. Z. Ahmed, L. T. Cumberland, N. N. Klimov, I. M. Pazos, R. E. Tosh & R. Fitzgerald, "Assessing Radiation Hardness of Silicon Photonic Sensors," *Sci Rep 8*, 13007 (2018). https://doi.org/10.1038/s41598-018-31286-9.
46. K. Takeda, & K. Shiraishi, "Theoretical possibility of stage corrugation in Si and Ge analogs of graphite," *Physical Review B*, *50*(20), 14916–14922 (1994). https://doi.org/10.1103/PhysRevB.50.14916.
47. G.G. Guzmán-Verri, & L.C. Lew Yan Voon, "Electronic structure of silicon-based nanostructures," *Physical Review B*, *76*(7), 075131 (2007). https://doi.org/10.1103/PhysRevB.76.075131.

48. J. Prasongkit, R.G. Amorim, S. Chakraborty, R. Ahuja, R.H. Scheicher, V. Amornkitbamrung, "Highly Sensitive and Selective Gas Detection Based on Silicene," *The Journal of Physical Chemistry C*, *119*(29), 16934–16940 (2015). https://doi.org/10.1021/acs.jpcc.5b03635.
49. S. Showket, K.A. Shah, A. Naqash, & G.N. Dar, "Structural, electronic, and gas sensing properties of nanoporous based armchair silicene Nanoribbon: A first principles study," *Computational Condensed Matter 44*, e01101 (2025a). https://doi.org/10.1016/j.cocom.2025.e01101.
50. S. Showket, K.A. Shah, A. Naqash, & G.N. Dar, "Light-induced sensing characteristics of Silicene nanoribbon based device: a first-principles study," *Computational and Theoretical Chemistry 1252*, 115384 (2025b). https://doi.org/10.1016/j.comptc.2025.115384.
51. F. Alaee, F. Ostovari, & M.A. Sadeghzadeh, "Simulation of silicene-based photosensor for carbon-based gas molecules," *Physica B: Condensed Matter*, *718*, 417870 (2025). https://doi.org/10.1016/j.physb.2025.417870.
52. G.K. Walia, D.K.K. Randhawa, & K.S. Malhi, "Rise of silicene and its applications in gas sensing," *J Mol Model 27*, 277 (2021). https://doi.org/10.1007/s00894-021-04892-0.
53. M. Houssa, "The rise of silicene," *NPG Asia Mater*, *7*, e191 (2015a). https://doi.org/10.1038/am.2015.60.
54. V. K. Dien, W.-B. Li, K.-I. Li , N. T. Han, M.-F. Lin, "Electronic and optical properties of graphene, silicene, germanene, and their semi-hydrogenated systems," *RSC Advances 12*(54), 34851-34865 (2022). https://doi.org/10.1039/d2ra06722f.
55. G. Li, L. Zhang, W. Xu, et al. "Stable Silicene in Graphene/Silicene Van der Waals Heterostructures,' *Advanced Materials*, *30*(49), 1804650 (2018). https://doi.org/10.1002/adma.201804650.
56. A. Skelton, K.J. Noone, "The Case for the Anthropocene Epoch Is Stronger Than the Case for the Holocene Epoch," *Earth's Future*, *13*(5), e2024EF005719 (2025). https://doi.org/10.1029/2024EF005719.
57. A. Frank, D. Grinspoon, and S. Walker, "Intelligence as a Planetary Scale Process," *International Journal of Astrobiology 21*(2), 47–61 (2022). https://doi.org/10.1017/S147355042100029X.
58. S. Puiu, "*Ethical Dilemmas,*" In S. O. Idowu, R. Schmidpeter, N. Capaldi, L. Zu, M. Del Baldo, & R. Abreu (Eds.), Encyclopedia of Sustainable Management (pp. 1517–1522). (2023). Springer International Publishing. https://doi.org/10.1007/978-3-031-25984-5_570
59. L.G. Lundh, & L. Foster, "Embodiment as a synthesis of having a body and being a body, and its role in self-identity and mental health," *New Ideas in Psychology*, *74*, 101083 (2024). https://doi.org/10.1016/j.newideapsych.2024.101083.
60. A. Ibrahim, A. -H. Salifu, & C. Peprah, "Does governance matter when disaster looms? Zooming into proactive institutional measures for flood risk management," *International Journal of Disaster Risk Reduction*, *97*, 104021 (2023). https://doi.org/10.1016/j.ijdrr.2023.104021.
61. M. Carrigan & D.V. Porpora, "*Post-Human Futures：Human Enhancement, Artificial Intelligence and Social Theory,*" (2021). London. 1-186 (2021). eBook ISBN9781351189958. https://doi.org/10.4324/9781351189958.
62. S. Susen, "Reflections on the (Post-)Human Condition: Towards New Forms of Engagement with the World? " *Social Epistemology*, *36*(1), 63–94 (2022). https://doi.org/10.1080/02691728.2021.1893859.
63. Y.A. Fadeyev, "Radial Pulsations of Stars at the Stage of the Final Helium Flash," *Astronomy Letters 45*, 655–663 (2019). https://doi.org/10.1134/S1063773719100037.
64. P. Plait, "Will the Milky Way and Andromeda Galaxies Ever Collide?" *Scientific American 331*(5), 80 (2024). https://doi.org/10.1038/scientificamerican122024-1HB3jIMUgbJOmi9m3CF2Ve.

Author Biography

doi:10.20944/preprints202603.0724.v1



Mr. Tianxi Sun（孙天锡）is currently a Professorial Senior Engineer in China. He was born in Suzhou, Jiangsu Province, China on November 4, 1945. He graduated from East China Normal University in Shanghai in 1968. He formerly worked for the East China Hydroelectric Power Survey & Design Institute and served at the Suzhou Ecological Environment Bureau until his retirement in 2005. He has completed several interdisciplinary studies, such as the following: Sun T.X. (2022). Hydrogen ice within lunar polar craters. *International Journal of Hydrogen Energy 47*, 34825 - 34830. https://doi.org/10.1016/j.ijhydene.2022.08.071.