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Concept to the Living Space

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Abstract

Humanity, as a part of the biosphere, has disrupted its equilibrium with Earth's system, inevitably leading to a critical juncture that demands a fundamental choice and a radical change in behavioral strategy. On an individual level, if a person does not believe in the existence of an afterlife, death, and hell, they are likely to choose hedonism, which would result in the extinction of humanity without leaving behind any intelligent beings. However, if a person is allowed to die, experience the afterlife, and then be resurrected while retaining the memory of that experience, their behavior would shift—prioritizing the bliss of self-development over mere pleasure. Ethics dictate that all who have previously died must also be resurrected. Can current technologies provide sufficient living space for a constantly growing population? Yes, this is not only possible but has been feasible for some time. To mitigate risks, living space can be expanded through the use of space-faring starships, large enough to sustain billions of people comfortably on territories exceeding the size of India. Intergalactic ships could have surface areas surpassing that of Earth. Additionally, around stars, including the Sun, it is possible to use the material from a single planet to create spheres whose surface areas would vastly exceed that of the planet itself.

Keywords: Exponential Growth, Solar System Utilization, Resource Expansion, Dyson Sphere, Interstellar Travel, Technological Development, O'neill Colony, Shockwave of Intelligence, Rome Club.

Introduction

The natural law governing population growth is exponential. This arises from the simple condition that the annual population increase is proportional to the existing population size, mathematically expressed as:

$$dN / dt = \alpha N$$

The current hyperbolic growth of the global population, observed over at least several centuries, is driven not so much by biological factors as by social ones. According to this law, the annual population growth is described by the equation:

$dN / dt = \beta N^2$

By overcoming social crises, humanity can ensure "normal" exponential population growth by reasonably adjusting the value of α\alphaα. Under this law, the catastrophic overpopulation predicted by the hyperbolic model would never pose a threat to humanity. However, no one knows the true number of deceased individuals requiring resurrection or whether social crises can indeed be overcome. To balance these risks, it is necessary to expand living space through space-faring starships, intergalactic vessels, and Dyson spheres constructed around stars.

The fundamental question arises: does the development of humanity's productive forces outpace or lag behind population growth? A reliable index of productive forces is the total energy production across all forms. Historical data, spanning from the late 18th century to the present, as provided by Rose & Clark, indicate that energy production has closely followed an exponential growth pattern during this period. Within this framework, the annual energy production per capita globally is determined by the difference between the energy production growth curve and the population growth curve. This difference has grown steadily to date. However, in the near future, this situation may change dramatically for the worse. It is worth noting that recent global population increases have been predominantly driven by developing countries.

Since humanity's entry into space, approximately $6 \cdot 10^{19}$ ergs of energy have been produced every second, with this figure doubling every 20 years. This trend has remained stable for roughly 200 years. At this rate, energy production will increase a thousandfold within 200 years, reaching $3 \cdot 10^{22}$ ergs per second. This milestone could be reached even sooner due to the limited reserves of coal and oil, making a revolution in energy production through nuclear and thermonuclear technologies likely within the coming decades.

The energy output of $3 \cdot 10^{22}$ ergs per second corresponds to about 1% of the solar energy continuously reaching Earth. Further increases in energy production will inevitably alter Earth's thermal regime, potentially leading to severe consequences. Of course, solar energy will eventually be harnessed on a large scale, but its use is limited; likely, no more than 1% of the Sun's total energy radiation can be utilized.

It is undeniable that an ever-growing technological potential will, within a relatively short time, come into conflict with the finite natural resources of planet Earth. Even today, increasing attention is being given to the alarming imbalance between humanity and its surrounding ecological environment—the biosphere. Issues such as atmospheric, oceanic, freshwater, soil, and plant pollution are becoming critical. Unchecked, spontaneous development of productive forces could lead humanity to disaster.

Imagine a hypothetical spaceship on a long interstellar journey spanning many years. Its crew would undoubtedly treat their extremely limited resources — oxygen, food, fuel, etc.— with utmost care and prudence. Similarly, the consciousness of thinking individuals must increasingly embrace the notion that Earth is a vast spaceship traveling through the depths of an extremely "inhospitable" universe. This "spaceship" has conveniently settled into a stationary, nearly circular orbit around a steadily radiating yellow dwarf star, utilizing its energy.

However, no matter how vast Earth's resources may seem, they are finite. Its crew—us, the Earthlings—must constantly remember this. It is time to view Earth as a cradle and to create living spaces of unimaginable scale around the Sun, build interstellar vessels, intergalactic ships and develop similar living spaces around other stars.

Exploration of Star Systems and Galaxies

A defining feature of intelligent life on Earth is its propensity for expansion into the surrounding cosmic space. Humanity is fortunate to witness the onset of this process, which began with the launch of the first Soviet artificial Earth satellite. This milestone initiated the development of a space industry encompassing vast complexes of specialized enterprises. Today, near-Earth space reliably serves humanity, aiding in its practical endeavors.

However, humanity's expansion into space does not end there. Following the soft landing of the first Soviet unmanned automatic station on the Moon's surface and its transmission of unforgettable images of a lunar terrain scattered with rocks, Earth's satellite became the target of an intensive wave of exploration. A significant milestone in this journey was the landing of American astronauts Armstrong and Aldrin in the Sea of Tranquility on July 20, 1969, followed by subsequent Apollo missions. The time is approaching when a permanent station will be established on the Moon.

Nevertheless, the exploration of near-Earth space and the Moon is only the first step in humanity's conquest of the Solar System. We are already witnessing the next phase: remarkable missions of automated space stations to Venus, Mars, Jupiter, Saturn, and Uranus, including the soft landing of spacecraft on Venus and Mars. These outstanding achievements are fundamentally significant. Since the Solar System's formation, objects from one planet have now been sent to others. These are not merely objects but sophisticated creations of human intellect that, through human will, have altered the grand design of the Solar System — albeit on a minuscule scale for now.

There is, however, a fundamentally novel approach to addressing the challenge of interstellar and transgalactic travel at nearly the speed of light. In recent years, several authors have proposed this new idea, with Bussard providing the most comprehensive exploration. The concept involves utilizing the interstellar medium as both thermonuclear fuel and rocket propellant. Since interstellar gas primarily consists of hydrogen, a rocket could be equipped with a thermonuclear device that synthesizes deuterium nuclei from hydrogen nuclei. The construction of such a device is not prohibited by any known laws of physics, suggesting that such a thermonuclear reactor could eventually be built.

The distinctive feature of this type of jet-propulsion vehicle is the enormous surface area required to intake interstellar gas. Calculations show that the "surface density" of such a rocket must be 10^{-8} if the surrounding space contains one hydrogen atom per 1 cm^3. In general, the surface density of the rocket is inversely proportional to the concentration of interstellar gas n_H. For instance, if the rocket's mass is 100 tons and n_H=1n 1 cm^{-3}, the required intake surface area would be 10^{15} cm^2, corresponding to a radius of approximately 700 km. In regions of the universe where nH≤10^{-5}, the "intake radius" must be hundreds of times larger. While this presents a significant challenge, who can guarantee that this difficulty will not be overcome within a few centuries — or even sooner?

Imagine a cylinder with a radius of 700 km or more, spinning around its axis to create artificial gravity as needed. The interior surface area of over 3,000,000 square kilometers — exceeding the size of India, which had a population of over 1.4 billion in 2024 — could support billions of people on their journey to a star system. For intergalactic travel, the spacecraft's area and population capacity would be tens of thousands of times greater. Constructing such vessels is theoretically feasible using technologies available at the dawn of the 20th century.

Accelerating interstellar or intergalactic spacecraft to near-light speeds is conceivable, though for now, velocities significantly below the speed of light are more practical. One fundamental challenge of near-light-speed travel is the destructive potential of collisions with interstellar atoms and, especially, dust particles. At such speeds, each colliding hydrogen atom would resemble a cosmic ray particle with an energy of 10^{13} eV. If the interstellar space contains one hydrogen atom per cm^3, the energy flux from cosmic rays on the rocket's forward surface would amount to $3 \cdot 10^{23}$ eV/cm^2 or $2 \cdot 10^{11}$ erg/cm^2.

The resulting lethal radiation levels would be intolerable, even for trips to the nearest stars. Shielding the spacecraft with conventional materials may be ineffective, particularly given the low payload-to-fuel mass ratio for conventional rockets and the proportionality of the intake surface area to the spacecraft's mass in interstellar-medium-based propulsion systems. Collisions with interstellar dust particles at such speeds could prove catastrophic.

Nevertheless, these challenges do not imply that near-light-speed interstellar travel is unattainable, even in the near future. Just a century ago, the idea of human flight on heavier-than-air machines seemed entirely speculative. The history of science and technology demonstrates that when societal demand for an invention arises, and it aligns with scientific principles, its realization is inevitable, sooner or later. Moreover, the pace of scientific and technological advancement accelerates with each passing decade. Thus, there are no fundamental objections to the feasibility of jet-propulsion spacecraft traveling near the speed of light.

Already, humanity has the potential for eternal youth (Tkemaladze et al., 2001–2024). On such spacecraft (and elsewhere), individuals could avoid death from aging, preserve and enhance cognitive abilities, and accumulate centuries of experience, which is invaluable for undertaking risky journeys into uncharted worlds.

Mastering the Solar System

It is clear that after long journeys, every individual in human society would want to rest in a calm environment without cosmic surprises.

A single planet, Earth, or one similar to it cannot accommodate trillions of people. How many people can Earth sustain simultaneously?

Are there still unoccupied living spaces? Is it possible to create artificial living spaces? Humanity is already beginning to modify the "master plan" of the Solar System.

Venus and Mars now have artificial satellites.

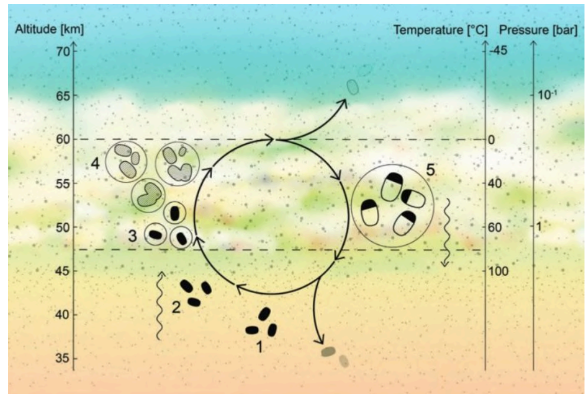
Venus, in particular, had no natural satellites of sufficient size for billions of years! Around Earth, thousands of satellites created by humans now orbit along various trajectories.

Humans are currently capable of triggering grand cosmic phenomena, such as auroras and magnetic storms, simply by detonating hydrogen bombs high above Earth's surface.

Unfortunately, the remarkable power of human intellect is not always used for the benefit of humanity. Nuclear explosions serve as a vivid example.

However, we are only witnessing the very beginning of humanity's entry into the cosmic era. Less than 100 years have passed since the event that heralded the start of this era. What lies ahead?

Picture 1. living conditions in the clouds of Venus



It is challenging to predict what transformations humanity might bring to the Solar System. For example, Morowitz & Sagan proposed a radical idea of "remodeling" Venus' atmosphere. This involves introducing a species of algae, Chlorella, into Venus' atmosphere. Rapidly multiplying, Chlorella would break down the abundant CO_2 molecules present there. As a result, Venus' atmosphere would gradually become enriched with oxygen. The chemical transformation would significantly reduce the greenhouse effect, leading to a drop in surface temperatures. Eventually, this "inhospitable" planet could become habitable. The process of colonizing Mars has already begun.

Picture 2. SpaceX Mars Base Architecture

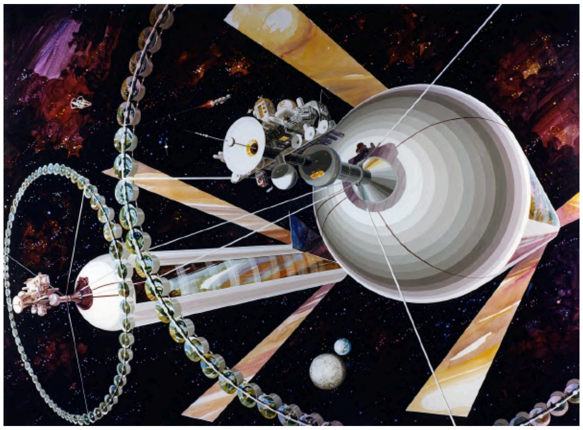
But why should humanity limit its activities to the Solar System? Earth intercepts only one two-billionth of the Sun's energy output. Sooner or later, humanity must harness "all solar heat and light" and begin spreading throughout the Solar System.

Even today, there exists an engineering design for a space settlement. Let us consider the oldest project proposed by the Princeton group of physicists and engineers led by O'Neill. This group developed a detailed technical plan for constructing enormous space colonies. The initial phase of the project envisions building a space station at one of the "Lagrangian points" in the Earth-Moon system—regions where gravitational forces balance out, allowing objects to remain stationary relative to Earth and Moon. This station would have a diameter of 1.5 kilometers, and its rotation would create artificial gravity equivalent to Earth's or any desired level.

It would include agricultural zones for growing vegetables and fruits, as well as facilities for livestock farming. Industrial plants would also be located there. Once completed, the station would become a self-sustaining system capable of hosting up to 10,000 people with a higher comfort level than on Earth.

The choice of the Lagrangian point is dictated by celestial mechanics, as objects can remain there indefinitely while orbiting Earth along the Moon's trajectory. Colonization of the Solar System will likely occur in stages, with robots handling most tasks in the harsh space environment. The project relies on current technology and extensively uses reusable space shuttles, reducing construction costs. Notably, much of the building material could be sourced from the Moon.

Picture 3. O'Neill cylinder (also called an O'Neill colony)



The construction timeline is estimated at 15–20 years, with costs 3–4 times higher than the Apollo program but lower than the Vietnam War, which lasted 8 years and claimed 50,000 lives.

Building such a space colony offers enormous benefits. Beyond unique opportunities for fundamental research, the station could become a major energy source for Earth. Solar energy captured by mirrors surrounding the station could be converted into microwave radiation and transmitted to Earth via special reflectors. This system boasts high efficiency (~70%), with power output exceeding that of massive oil pipelines.

From this station, humanity could move on to building even larger structures in space, hosting 40–50 million people in comfortable conditions. After small towns, the next phase involves transforming the asteroid belt. Energy for supporting robots and human life on modified asteroids could be drawn from solar panels or radioactive batteries.

These transformed asteroids could form chains of cities, eventually exhausting asteroid resources and turning to larger planets. This process could take hundreds of thousands to millions of years — an instant for immortal humans. A restructured Solar System could sustain 3×10^{23} people — 3.75×10^{13} times Earth's current population of 8×10^{9}. Freeman Dyson analyzed the quantitative aspects of humanity's transformation of the Solar System. Dyson highlights the rapid pace of scientific and technological development during the "technological era." Compared to astronomical and geological timescales, this development occurs over a very short timeframe.

However, a key limiting factor for scientific and technological progress is the finite availability of material resources. Presently, Earth's biosphere, with a mass of approximately 5×10^{19} grams, represents only one hundred-millionth of Earth's total mass. Humanity currently consumes about 1.8×10^{20} ergs of energy per second. Fossil fuel reserves, including coal and oil, are expected to deplete within the next century. The era of space exploration radically changes the resource paradigm.

At a sufficiently advanced stage of development, society will inevitably turn to extraterrestrial resources within the Solar System. Solar radiation, emitting 4×10^{33} ergs per second, becomes a primary energy source, while the masses of giant planets provide material resources. For example, Jupiter's mass is 2×10^{30} grams. Dispersing Jupiter's mass would require approximately 10^{44} ergs—equivalent to the Sun's energy output over 800 years.

Dyson suggests constructing a massive sphere, about 1 astronomical unit (150 million km) in radius, encircling the Sun. With a shell thickness providing 200 g of material per square centimeter, the Dyson Sphere could be habitable. Its surface area would be about 1 billion times that of Earth, supporting 3×10^{23} inhabitants.

Dyson notes an intriguing correlation between planetary masses, artificial biosphere thickness, solar output, and technological development timescales. Within 2,500–3,000 years, intelligent beings are likely to create artificial biospheres surrounding their stars.

Picture 2. Dyson sphere

The time required to utilize all the material resources of the Solar System under such exponential growth is estimated to be less than 500 years. Even if we take into account possible delays in development due to the adoption of new technologies and assume a very "slow" growth rate—1% per year — the characteristic time for our civilization to fully develop the Solar System would still not exceed 2500 years.

It seems evident that approximately 1000 years of development will bring about the same problem we face today — the limitation of resources within a finite system under exponential growth of development parameters. Overcoming this contradiction will inevitably push a technologically advanced population to exploit resources first in the nearest regions of the Galaxy and then throughout our entire stellar system. This will initiate a process of "diffusion" of humanity into the Galaxy, accompanied by the intelligent transformation of stars and, particularly, the interstellar medium. However, it would be more accurate to describe this process not as "diffusion" but as the propagation of a "strong shock wave" of intelligence through inert matter.

A good model for such a process is Huygens' well-known construction describing the propagation of a spherical wave of light. Each point in space reached by the disturbance becomes the center of secondary spherical waves. In our case, such a "point" would be a suitable star, around which arriving colonists, using local resources, would build an artificial biosphere — a Dyson sphere.

The propagation speed of the disturbance will be approximately $v = R / t^2$, where $t^2 \approx$ 1000 years—the characteristic time required to construct a Dyson sphere, and $R \approx 10$ light-years — the average distance to suitable stars (e.g., spectral class G stars). From this, it follows that $v \approx 3{,}000$ km/s, i.e., 1% of the speed of light (c). In this case, considering the maximum size of the Galaxy (about 100,000 light-years), the time required for colonization and transformation of the entire stellar system will be only 10 million years. This value is extremely small compared to the shortest characteristic timescales in the Galaxy. Note that at this stage of development, the characteristics of civilization will no longer grow exponentially with time (due to the finite speed of light) but instead will follow a power-law growth — initially as t^3, and later more slowly, as t^2 — an observation that is not difficult to demonstrate.

It should be emphasized with absolute certainty that the current state of natural sciences, as well as the experience gained during 30 years of the space era, excludes the possibility of natural causes that would make such development fundamentally impossible. The scenario described above (including interstellar flights of automated stations with eternally young intelligent beings) does not contradict any known laws of nature.

Discussion

A comprehensive mathematical study of living space was conducted by a group of highly competent specialists known as the "Club of Rome." The complexity of the problem lies in the interdependence of humanity's developmental parameters, such as per capita industrial production, environmental pollution, and others. It is also important to consider the inertia inherent in all global processes, including economic growth, population expansion, and environmental degradation.

Mathematically, the task reduces to solving a system of thousands of simultaneous differential equations—a challenge manageable only with modern computational technology. The branch of science addressing this issue is known as systems analysis.

The first step involved a careful assessment of Earth's resources, which are irreversibly consumed in the process of technological progress. Economic and statistical data were then used to project resource production rates and their dependence on time, ultimately estimating the "depletion time" of each resource.

Members of the "Club of Rome" devoted particular attention to the problem of environmental pollution caused by human activity. It is crucial to note that waste treatment is exceedingly expensive, especially if the goal is to achieve sufficiently clean emissions—which is precisely what is needed. The authors of this study developed several models for the future development of human society.

The first is the "standard" model, which assumes that development continues as it has in the past—essentially answering the question, "What happens if nothing changes?" The results of their analysis are alarming. After 2030, a catastrophic scenario unfolds: population numbers and industrial output rapidly decline, while pollution levels soar. Civilization collapses, and with it, pollution also disappears.

Another intriguing model explores the development of civilization under the assumption of unlimited resource availability. In this case, catastrophic environmental pollution leads to collapse. Searching for solutions, the "Club of Rome" authors propose strict control over birth rates and halting industrial growth. While this approach may delay collapse, it merely postpones it by two to three centuries. The concept of the "golden billion"—a select population living in relative comfort—would only delay humanity's extinction by a few generations.

It is worth noting that the models described above are limited—they do not consider intelligence as a factor for space expansion. Furthermore, the extreme inequality in global development, the presence of two antagonistic systems (e.g., the United States and China) along with their proxy states, and the acute problems of developing countries are ignored. Additionally, the models overlook the real possibility of wars in a world divided into competing blocs. These factors are likely to exacerbate the situation.

As a remedy to the anticipated catastrophe, the "Club of Rome" proposes a fundamental shift in civilization's strategy: abandoning growth in favor of a strictly regulated equilibrium (the concept of a "steady-state" civilization).

Геловани et al. mathematically demonstrated that the "global equilibrium" proposed by the "Club of Rome" cannot prevent a crisis; it merely postpones it by a hundred to two hundred years. In fact, the models analyzed by Western authors do not allow for "non-trivial" stationary solutions. The "trivial" solution, translated from mathematical terms, equates to death (i.e., zero values for all global model parameters, such as production levels, population size, and pollution).

As an alternative, Геловани proposed and calculated a model that eliminates "collapse" not by halting growth but through intelligent management of capital investments. However, this approach requires redirecting a significant portion of these investments toward combating pollution, restoring resources, and mitigating soil erosion. How exactly this should be done remains unclear.

Essentially, this model, which permits a "non-trivial" stationary state, envisions transforming our planet into a spacecraft-like system on an indefinite mission: every gram of matter accounted for, and all resources regenerated.

Despite its innovative approach, Гелованi's model likely fails to eliminate the problem of "collapse" entirely. Only halting industrial growth and implementing strict regulations on resource use and regeneration — combined with allocating the lion's share of national income to combating environmental pollution — may offer a viable solution.

However, time is running out, and urgent action is required.

Conclusions

All the arguments presented above consider humanity's development within the finite confines of the Solar System, where the availability of resources and energy imposes natural limits to growth. However, is this assumption of confinement justified in the long term? Given humanity's demonstrated capacity for technological advancement, coupled with the exponential growth of scientific knowledge, it is plausible to envision a transition from terrestrial dependence to an interplanetary and eventually interstellar civilization.

Under a framework of sustainable development and advanced resource management, humanity can progressively shift industrial production and energy harvesting into space. Large-scale engineering projects, such as Dyson spheres or orbital habitats, could facilitate the construction of self-sustaining artificial biospheres capable of supporting populations orders of magnitude larger than Earth's current carrying capacity. This approach not only alleviates the pressure on terrestrial ecosystems but also preserves Earth as a cultural and ecological sanctuary.

In such a scenario, Earth could evolve into a protected zone dedicated to intellectual, artistic, and scientific pursuits. With its pristine environment safeguarded, it would serve as a cradle of philosophical inquiry, creative exploration, and cutting-edge research. Meanwhile, technological outposts scattered across the Solar System—and eventually the galaxy—would extend humanity's reach, ensuring survival, growth, and adaptation in the face of cosmic challenges.

Moreover, the rapid dissemination of intelligent systems across interstellar distances, akin to a "shockwave" of reason propagating through space, represents a natural trajectory for a technologically advanced species. This diffusion process could transform barren star systems into vibrant hubs of life and activity, embodying the principles of sustainable expansion and intelligent resource utilization.

Finally, it is important to emphasize that no fundamental physical laws prohibit the realization of these scenarios. The principles of thermodynamics, energy conservation, and relativity impose constraints, but they do not render interstellar travel or large-scale cosmic engineering impossible. Decades of space exploration have already validated the feasibility of extended operations in extraterrestrial environments, while emerging technologies hint at even greater possibilities.

Therefore, the transition from a resource-limited terrestrial society to a distributed, spacefaring civilization is not only conceivable but potentially inevitable. The described vision of interstellar expansion — powered by intelligent automation, sustainable technologies, and artificial biospheres — stands firmly within the boundaries of known science and represents a compelling pathway for humanity's long-term survival and evolution.

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