Mediterranean Archaeology and Archaeometry, Vol. 18, No 4, (2018), pp. 297-306
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DOI: 10.5281/zenodo.1477986

OUR FUTURE OFF–EARTH AND THE ROAD TO THE STARS

Chris Impey*[1]

[1]College of Science, University of Arizona, Tucson, Arizona 85721, USA

Received: 16/02/2018
Accepted: 20/06/2018
**Corresponding author: Chris Impey (cimpey@as.arizona.edu)*

ABSTRACT

Fifty thousand years ago, humans demonstrated their urge to explore by leaving Africa and radiating out across the planet. About fifty years ago, they mastered the technology to leave the planet for the first time. Now, we are poised to venture out into the Solar System and beyond, to the stars. Only 600 people have been in Earth orbit, and just 12 have stood on another world. For most of its history, the "Space Race" was a superpower rivalry born out of the Cold War. Now, new countries involved and a burgeoning private sector has bold plans for tourism and commerce beyond the Earth. The next fifty years should see colonies on the Moon and Mars, the mining of asteroids, a space elevator, and increasing human exploration of the Solar System. Space travel is poised to transition from being the activity of an elite few to being a broader aspect of human culture. The dream of human travel to the stars may finally be within reach.

KEYWORDS: space travel, exploration, rockets, astronauts, space tourism

1. THE URGE TO EXPLORE

Epic animal migrations are driven by climate, the availability of food, or mating, and almost all animal migrations are seasonal. Humans are the only species that moves systematically and purposefully over huge distances, in multi–generational migrations, for reasons not tied to the availability of resources. The itch that led our ancestors to risk everything to travel in small boats across large bodies of water like the Pacific Ocean is related to the drive that will let us colonize Mars (Figure 1). Its origins lie in a mixture of culture and genetics.

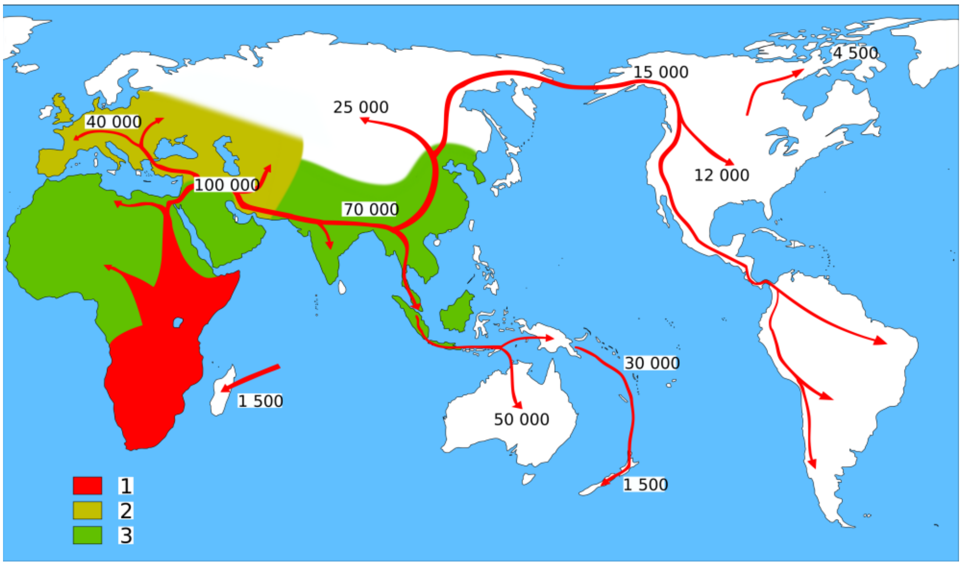

Figure 1. Map of early human migrations, based on DNA in mitochondrial genomes. The migration routes are marked in years before the present day. Different colors indicate homo sapiens (1), Neanderthals (2), and early hominids (3). Credit: Human Genographic Project, National Geographical Society.

Human children spend a proportionally longer time in a world where their development is sheltered and facilitated by adults (Gopnik et al., 1999). We play by creating hypothetical scenarios that allow us to test hypotheses—acting in effect like miniature scientists. Children are fearless hypothesis machines. Mental exploration later becomes exploration of the physical environment after the child develops the necessary motor skills. The exploration of hypothetical scenarios through play isn't needed for survival and the tendency for mental exploration is peculiarly human. Restlessness isn't only in our minds; it's also in our genes.

We share more than 95% of our DNA with monkeys and apes, so have great commonality with our most recent ancestors. Yet certain developmental genes gave us an edge over apes and other hominids; we have lower bodies built for walking long distances, hands that are better for manipulating objects, and brains with larger language and cognition regions. These genes are regulated by regions of DNA that used to be labeled "junk" but are now recognized as being keys to understanding how a species evolves.

One particular gene has received a lot of attention because of its central role in controlling one of the most important neurotransmitters. DRD4 is one of the genes that control dopamine, a chemical messenger which influences motivation and behavior. People with one of the variants of this gene, called 7R, are more likely to take risks, explore new places, seek and crave novelty, be extraverts, and be hyperactive. About one in five of the population carries DRD4 in the 7R form. Intriguingly, the 7R mutation probably first occurred about 40,000 years ago, soon after the exodus from Africa, when humans began fanning out across Asia and Europe. Other studies explicitly tie 7R to migration. Among the largely stationary populations of Asia, only 1% currently has 7R, while the prevalence is 60% in present day South Americans, whose populations traveled large distances from Asia 16,000 years ago (Matthews and Butler 2011).

Is there an "exploration gene?" No. Genes work in combination with each other and behavior is sculpted by the environment, so genes are not destiny and no single gene can hard–wire us for exploration. Also, unknown situations can be fraught with danger so a gene that spurs exploration doesn't necessarily offer a selective advantage. Moreover, when this gene is expressed it can have a downside. People with the 7R variation are over two times more likely to suffer from ADHD, 50% more likely to be sexually promiscuous (which is an evolutionary advantage), and they're also prone to alcoholism and drug addiction. The safe functioning of any hunter–gatherer society requires intensive cooperation and stable social relationships; too much thrill–seeking would be dangerous and disruptive.

However, in situations of resource scarcity or stress, this particular mutation has advantages. Owners of 7R are not only comfortable with change, they startle less easily (Roussos et al, 2009). They also use less emotion in making decisions and they're less impacted by the negative emotions of others. Low emotional reactivity and high emotional endurance are valuable traits for a human in a perilous, new environment, as is the ability to plan and solve complex problems when faced with a threat. The adventure genotype may even protect against stress, anxiety, and depression. Even if they're only present in a fraction of the population, traits that favor adventurousness are self–reinforcing. If the 7R mutation has slightly higher frequency in a population that migrates, that frequency will increase in a finite gene pool. Mobility and dexterity are enhanced as they are expressed. The best nomads will encounter new sources of food and new possibilities for enhancing their lifestyle. The best users and makers of tools will be spurred come up with new tools and novel applications of existing tools. The fulcrum of this feedback loop is our one attribute that's unparalleled: a big brain.

2. SPACE VISIONARIES

The first space visionary was a mid–level official from the Ming Dynasty with an obsession for getting close to the stars. Wan Hu was from a rich family and his path was clear to becoming a high government official, but bureaucracy bored him. He was more interested in the Chinese traditions of gunpowder and firecrackers, which had been used for centuries during religious festivals and for entertainment. He yearned to have a bird's eye view of the world. Dressed in his finest clothes, Wan Hu sat in a sturdy bamboo chair with 47 rockets attached (Figure 2). He held the strings of two kites to guide him on his flight. On his signal, 47 assistants lit the fuses and rushed for cover. According to legend, a tremendous roar was accompanied by billowing clouds of smoke. When the smoke cleared, Wan Hu was gone. Rather than becoming China's first astronaut, Wan Hu was probably obliterated from the explosive force of so many rockets detonated at once (Zim 1945). Despite this spectacular failure, the Middle Kingdom was far ahead of other countries in developing rockets, beginning a long tradition that twinned rocketry with warfare.

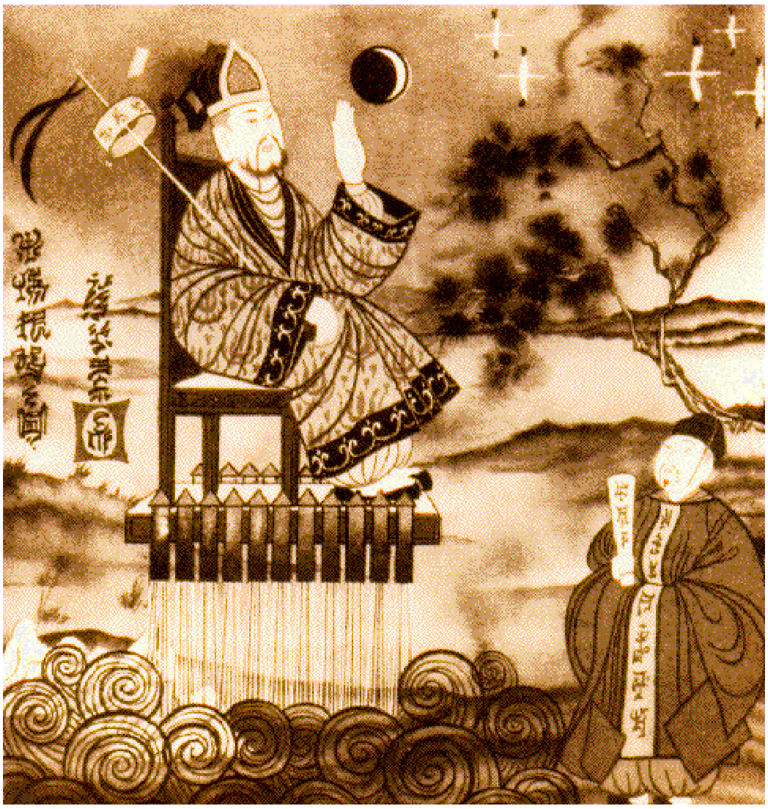

Figure 2. Wan Hu was a legendary Chinese government official of the middle Ming Dynasty (16th Century), who tried to become the world's first astronaut by attaching 47 rockets to a specially constructed chair. Credit: United States Civil Air Patrol and NASA.

The first true rockets were probably accidents. In the first century A.D., the Chinese learned how to make simple gunpowder from saltpeter, sulfur, and charcoal dust (Lethbridge, 2005). They put this mixture into bamboo tubes and tossed them into a fire to make explosions during religious festivals. Some of tubes may have failed to explode, instead skittering out of the fire propelled by gas from the burning gunpowder. Over the next few centuries, rockets continued to appear in harmless firework celebrations, but they showed more promise as military weaponry. Europeans soon learned the secrets of rockets and started to improve the technology. Their neglect of science and technology caused the Chinese to lose their edge. By the late 14th century European nations had caught up. Rockets were relegated to firework displays. Wan Hu's dreams of traveling to the stars were forgotten.

Konstantin Eduardovich Tsiolkovsky was born into an impoverished family of Polish immigrants in 1857 in a small Russian town, the fifth of eighteen children. At the age of ten he developed scarlet fever, leaving him deaf and isolated. By age fourteen his mother had died and he had given up formal schooling. A reclusive teenager, he spent hours at a local Moscow library where he studied physics and astronomy. At the library he was strongly influenced by Nikolai Fyodorov, a futurist who advocated radical life extension and immortality and who thought that the future of humanity lay in space. He also stumbled on the works of Jules Verne and became inspired by Verne's tales of space travel. Tsiolkovsky's family recognized his talent but they worried that he was studying obsessively and forgetting to eat (Lewis 2008).

Tsiolkovsky became a math teacher in a small provincial school outside Moscow. In his spare time he wrote science fiction, but soon became more interested in the concrete problems of space travel. He realized that passengers would not survive the acceleration forces of a cannon, the fictional method Jules Verne imagined to get travelers to the Moon. As a teenager, he constructed a centrifuge to test the effects of strong gravity. Chickens procured from local farmers were his test subjects. Later, he built the world's first wind tunnel in his apartment and conducted experiments on the aerodynamics of spheres, disks, cylinders, and cones. But he had no funding for his work and, isolated from scientists, most of his insights were theoretical.

In 1897, Tsiolkovsky devised an equation that relates the changing mass of a rocket as it burns its fuel and the speed of the gas as it exits (Tsiolkovsky 1903). From this starting point he recognized the critical role of a nozzle in forcing the gas out at high velocity, and he predicted the need for multi–stage rockets to overcome the Earth's gravity. He also designed fins and gas jets to control the trajectory, pumps to drive fuel into the combustion chamber, and mechanisms that used propellant to cool the rocket in flight. His fertile mind came up with designs for dirigibles, metal jet aircraft, and hovercrafts. Hearing about the newly constructed Eiffel Tower triggered the idea of a space elevator as a way of getting into orbit without a rocket (Moore, 1813).

In the 1920's, the young physicist Hermann Oberth was unaware of Tsiolkovsky's work, but he too dreamt of space travel. Like the Russian, Oberth was inspired by Jules Verne, rereading the novels to the point of memorization. He dabbled with rockets as a child and by 1917 his expertise had grown such that he fired a rocket with liquid propellant as a demonstration for the Prussian Minister of War. His doctoral thesis titled "The Rockets to the Planets in Space" later became an essential contribution to rocket science but it was initially rejected. Oberth was fiercely critical of German education, saying it was "like an automobile which has strong rear lights, brightly illuminating the past. But looking forward, things are barely discernible" (Stange, 2000).

Like Tsiolkovsky, Oberth worked outside academia for the majority of his career, earning a living as a school teacher. He was a leading member of a German amateur association, whose members scavenged any materials they could find for their rockets as Europe descended into an economic depression. In 1929, Oberth was a technical advisor to the film pioneer Fritz Lang on "The Woman in the Moon," the first film ever to have scenes shot in space. He lost an eye during a publicity stunt for the film. That same year, he conducted a captive firing of his first liquid–fueled rocket engine. One of his assistants was 18–year–old Wernher von Braun, who was later to feature prominently in our efforts to reach space.

The first to launch a liquid fuel rocket was American Robert Goddard (Figure 3). As a boy, Goddard was thin, frail, and subject to pleurisy, bronchitis, and stomach problems. He spent hours holed up in the local public library, where he was transported by the science fiction of H.G. Wells. Goddard fixed his inspiration to a day when he was 17 and he climbed a cherry tree to remove dead limbs: "I imagined how wonderful it would be to make some device which had even the *possibility* of ascending to Mars, and how it would look on a small scale, if sent up from the meadow at my feet… I was a different boy when I descended the tree from when I ascended" (Goddard, 1966).

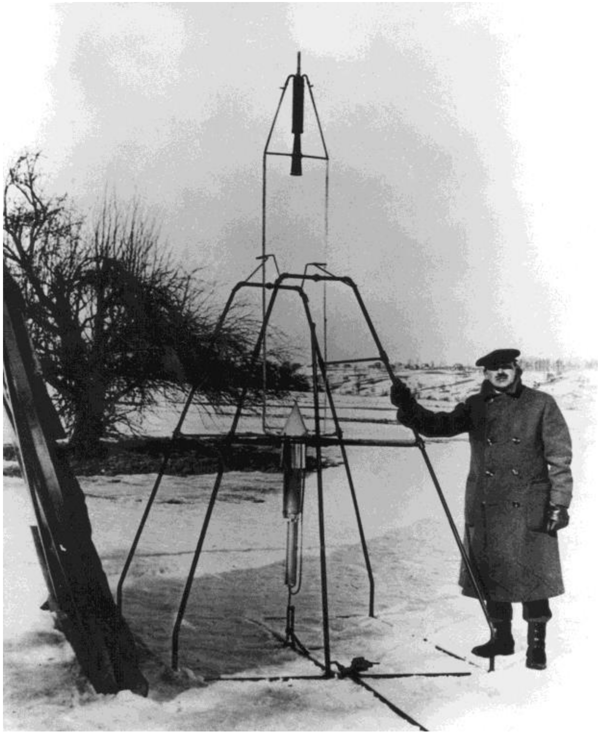

Figure 3. Robert Goddard is bundled against the cold of a 1926 New England winter as he stands beside the launching frame of his most notable invention. The liquid fuel of this rocket was gasoline and liquid oxygen, contained in the cylinder across from Goddard's torso. Credit: Goddard Space Flight Center and NASA.

In 1914, Goddard registered the patents for a liquid fuel rocket and a multi–stage rocket, the first of his more than 200 patents. He was a hands–on experimenter as well as an expert physicist. Liquid fuel rockets are finicky because the volatile fuel and oxidizer must be injected into a combustion chamber at a carefully controlled rate. On a bitterly cold spring morning in 1926, Goddard achieved success with a small liquid propellant rocket dubbed "Nell." Launched from his Aunt Effie's farm, it traveled for 184 feet in a flight that lasted less than three seconds, landing in a cabbage field. Over the years, he conducted more three dozen test flights, refining his designs and techniques until he reached altitudes of several miles. He formed a lifelong friendship with Charles Lindbergh, who shared his vision. Nevertheless, the world was not quite ready for rockets. Goddard's seminal paper from 1919, "A Method of Reaching Extreme Altitudes," was ridiculed by the press and fellow scientists. He was only vindicated after his death in 1945.

3. THE SPACE RACE

Warfare and space exploration merged again in the 1940's. Goddard had worked using small grants from the Smithsonian and Guggenheim foundations; no government agency showed interest and the military was particularly dismissive. But America's future adversaries were very interested in Goddard's rocketry. During the 1930's, a German military attaché working in the U.S. sent a report on Goddard's work back to the military intelligence agency, and the Soviets got information from a KGB spy embedded in the U.S. Navy Bureau of Aeronautics. Towards the end of World War II, Goddard got to inspect a captured German V2 ballistic missile. The V2 was far more advanced than any of Goddard's rockets, but he was convinced the Germans had "stolen" his ideas. The architect of the V2 was the most controversial figure in the history of rocketry: Wernher von Braun.

As a young boy, von Braun got hooked on rockets. Inspired by Germans setting land speed records in rocket–propelled cars, the 12–year–old caused major disruption in a crowded street. Echoing Wan Hu, he attached a dozen of the largest skyrockets he could find to a toy wagon. Rather than riding the wagon as Wan Hu had ridden his sedan chair, von Braun lit the fuses and stood back. He was thrilled with the results: "It performed beyond my wildest dreams. The wagon careened crazily about, trailing a tail of fire like a comet. When the rockets burned out, ending their sparkling performance with a magnificent thunderclap, the wagon rolled majestically to a halt." The police who arrived on the scene were less impressed; they took the young boy into custody (Neufeld, 2006)

At age 18, von Braun began his long tutelage with Hermann Oberth and that same year he attended a talk by a pioneer of high altitude ballooning, telling him, "You know, I plan on traveling to the Moon at some time." von Braun was twenty one when Hitler came to power. He later claimed that he had been apolitical and disinterested in the world around him. But his uncritical patriotism meant that, at best, he was surprisingly naïve about the ramifications of his work and, at worst, he was complicit in death and destruction. He joined the Nazi Party and the SS, and photos exist of him donning those uniforms and posing in the company of senior Nazi party members.

In early 1945, as Allied forces moved deep into Germany, the SS moved von Braun and his team to the Bavarian Alps, with orders to execute them rather than let them fall into enemy hands. He was able to slip away and surrender to a private from the 44th Infantry Division. Von Braun was at the top of the Black List of German scientists and engineers targeted for interrogation by U.S. military experts. When the fog of war lifted, von Braun had been rehabilitated. The U.S. Intelligence agencies created a false employment history for him and expunged his party membership from the public record. He was given a security clearance. In Germany he had thousands of engineers reporting to him, but in the United States he had a small team and was starved of resources (Neufeld, 2007). Although the post–war years were frustrating for von Braun, at least he had a new start and he was free to pursue his dreams of space.

At the end of the war, the Russian counterpart to von Braun was the equally brilliant Sergei Korolev. He started by reverse engineering the V2, but quickly developed his own designs, leading to a 100–ton engine of unprecedented power. Korolev spent six years in prison as a result of Stalin's purges and his treatment there gave him serious health problems throughout his life. The Soviets referred to him only as the "Chief Designer" during the Cold War and his identity wasn't revealed in the West until after his death in 1966.

Mistrust between the United States and the Soviet Union deepened after the war. The United States lost its monopoly on the atomic bomb and watched helplessly as the Soviets annexed European countries to form an "iron curtain" that stretched from the Baltic to the Adriatic. The role of ideology in the Space Race has been summarized by journalist and historian William Burrows: "The cold war would become the great engine—the supreme catalyst—that sent rockets and their cargoes far above Earth and worlds away. If Tsiolkovsky, Oberth, Goddard, and others were the fathers of rocketry, then the competition between capitalism and communism was its midwife" (Burrows, 1998). The visionaries never gave up their ambitions for humans to leave the Earth. But dreams of space travel were overshadowed by nightmares of nuclear holocaust.

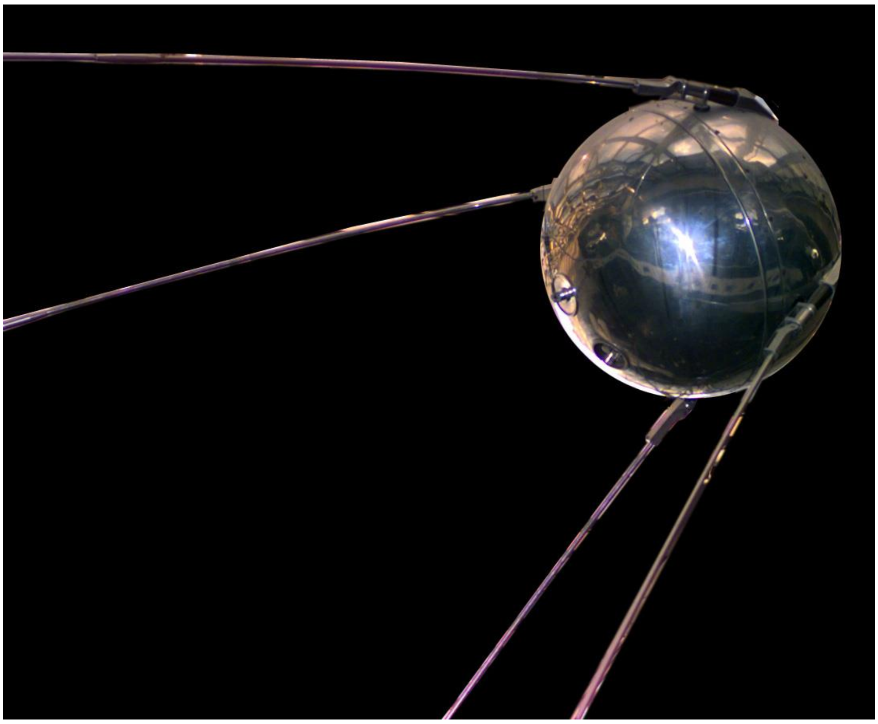

Figure 4. Sputnik 1 was the first artificial satellite to orbit the Earth. Launched by the Soviets into a 90–minute, low orbit in October, 1957, it transmitted signals for three weeks before burning up in the Earth's lower atmosphere. Sputnik triggered the Space Race. Credit: NASA.

The "Space Race" began when the United States and the Soviet Union developed ballistic missiles that could launch objects into space. It was kicked off in 1955 by announcements only four days apart that both nations were planning to launch artificial Earth satellites (Siddiqi, 2000). Stockpiles of nuclear weapons grew rapidly; the underlying goal was the capability to target and destroy any city in the opposing country within hours. On October 4, 1957, the Soviets shocked the world when they launched into orbit a beeping metal sphere the size of beach ball and the weight of an adult man: the satellite Sputnik (Figure 4). Stakes in the Space Race suddenly became very high.

Although it was the height of the Cold War, and space could easily have become the exclusive preserve of the military, the cool head of the Commander–in–Chief prevailed. Eisenhower was playing catch–up with a well–funded and better organized adversary. He knew that the best innovation would come from a national space agency rather than small groups often working in competition and in isolation. As a former general, Eisenhower knew enough about military bureaucracy to prefer a civilian organization. On October 1, 1958, he established NASA as a civilian organization for the peaceful exploration of space. The new agency began with 8200 employees and a budget of $340 million. Its charter in the Space Act had objectives that included expanding knowledge of space, improving space vehicles, preserving the leadership of the United States in space science and technology, and collaborating with our international partners and allies. The Space Act was signed a little less than a year after the Soviet beeps that rocked the world.

NASA was created in a context of superpower rivalry. Its early years were marked by an unprecedented build–up in the number of nuclear weapons and a real fear that space would be militarized. Yet NASA had a peaceful mission and it was subject to oversight by Congress. There were visionaries throughout the agency who went to work every day believing that space travel fulfilled a noble human aspiration.

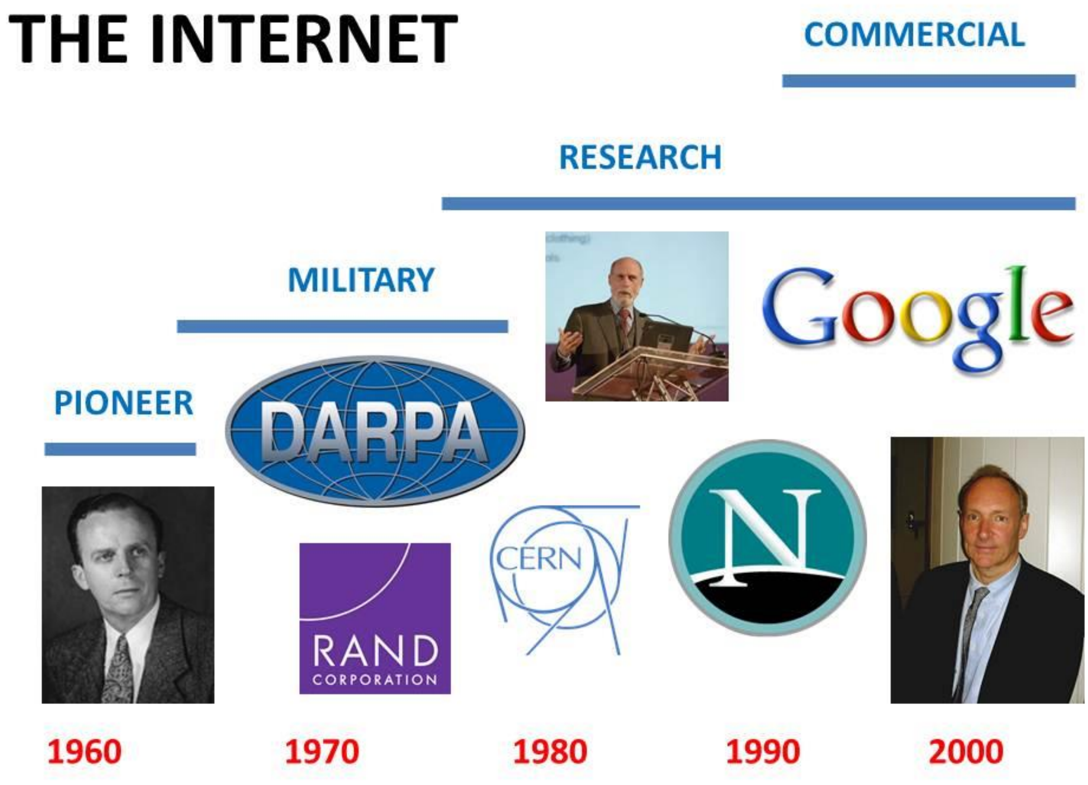

Figure 5. The Internet had pioneers who foresaw a worldwide inter–connected communication system. It was incubated by the military and in research labs before it emerged into the private sector. Credit: Chris Impey.

4. THE NEW ENTREPRENEURS

Sixty years after start of the Space Age, only 600 people have experienced zero gravity in Earth orbit, and just 12 Apollo astronauts have set foot on another world. We are witnessing a transition from an activity run by governments and executed by the Military–Industrial "complex" to an activity run dynamic private sector companies. The current crop of space entrepreneurs like Elon Musk, Jeff Bezos and

Richard Branson are pinning their hopes for profitability on space tourism. The initial revenue will come from expensive trips for the elite, with the presumption that as the costs come down, a larger audience will be in the market for the singular experience of zero gravity and a view of the entire Earth. This is the progression followed by civil aviation between the 1930's and the present day.

An analogy can be made between the history of the Internet and the history of space exploration. In each case, there were pioneers who envisaged a future far beyond the early capabilities. Each type of activity was incubated by support from the U.S. military. Each progressed with government support to universities and research institutes. But rapid innovation required new investment by the private sector. The Internet is now so ubiquitous it is hard to imagine its humble origins (Figure 5).

The "take–off" year for the Internet was 1995, when the first Internet Service Providers formed, Amazon was founded, and two students at Stanford envisaged the search algorithm behind Google. In space, we may be witnessing the same type of transition; 2016 was the first year where most space launches were commercial (Figure 6).

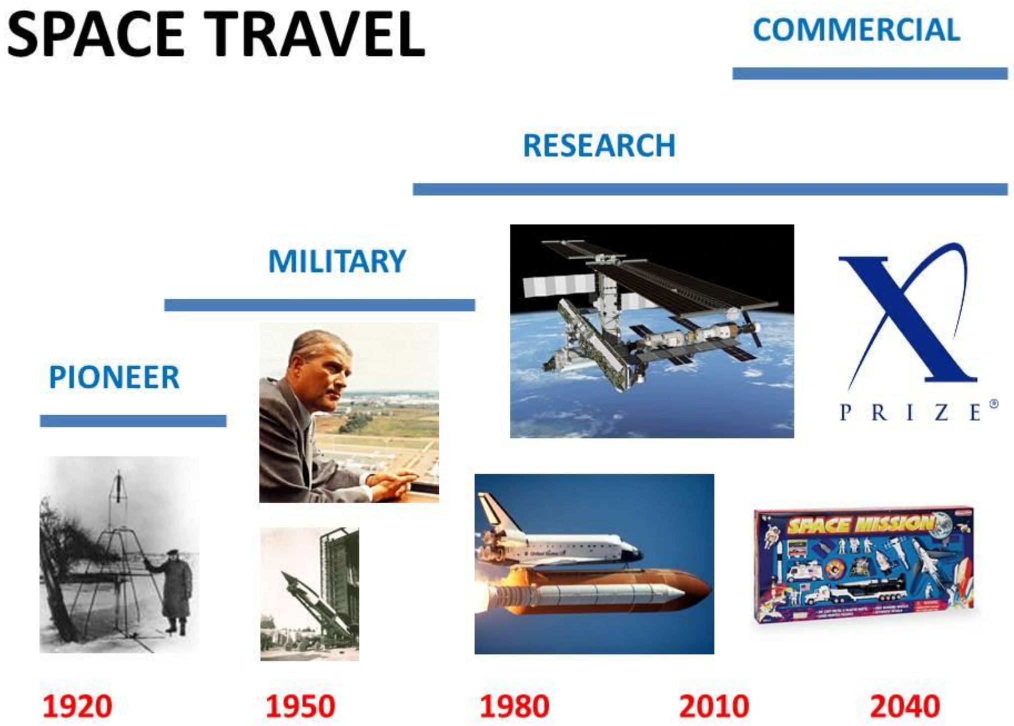

Figure 6. The Space Program also had visionaries who foresaw a permanent human presence in space. Progress was spurred by military superpower rivalry and fostered by NASA. Private investment means the space industry sits now where the Internet was in the mid 1990's. Credit: Chris Impey.

These brief jaunts a few hundred miles up are far from the early visions of space travel. What are the challenges that might want to make us find a new home in space? The best metric for proximate danger is the Bulletin of the Atomic Scientists. Starting in 1947, a group of scientist and engineers created a Doomsday Clock to show how far we were from apocalypse. As the threat of nuclear holocaust receded, the proximity of the clock to midnight started to take into account the possibility that through climate change, biotechnology, or cyber–technology we could cause irrevocable harm to our way of life and the planet. The clock sat at two minutes to midnight in 1953, at the nadir of the Cold War. It receded to 17 minutes from minute with the fall of the Soviet Union. But now it once again reads two minutes to midnight because of a surge of nuclear weapons in the hands of small, unstable countries, and the sense that climate change may have passed a tipping point.

5. LIVING OFF–EARTH

Many voices have weighed in on leaving the Earth. In 1895, the rocket pioneer Konstantin Tsiolkovsky said "Earth is the cradle of humankind, but one cannot live in the cradle forever." Carl Sagan put in this way a century later: "Since, in the long run, every planetary civilization will be endangered by impacts from space, every surviving civilization is obliged to become spacefaring—not from exploratory or romantic zeal, but for the most practical reason imaginable: staying alive" (Sagan, 1994). Science fiction writer Larry Niven was more succinct, "The dinosaurs became extinct because they didn't have a space program." We may be able to fend off impacts from space but Stephen Hawking sounds the alarm about other threats: "It will be difficult enough to avoid disaster in the next hundred years, let alone the next thousand or million. Our only chance of long–term survival is not to remain inward–looking on planet Earth, but to spread out into space."

A mass exodus from Earth is implausible. After all, it costs $50 billion to send a dozen people to the Moon for just a few days. Elon Musk may claim he'll reduce the price of a trip to Mars to $500,000, which is a hundred thousand times less, but that seems like a fantastic claim at the moment. If the Earth becomes contaminated or inhospitable we'll have to live in bubble domes, fix it, or suffer through it. But in this century a first cohort of adventurous humans will probably cut the umbilical and live off–Earth.

How many people does it take to start over? In conservation biology and ecology there's a term called "minimum viable population." This is the lower bound on the population of a species in the wild such that it can survive natural disasters and demographic and genetic variations. In animal population studies, about 500 adults are required to avoid inbreeding, and 5000 adults are required to allow a species to pursue a typical evolutionary lifespan from origination to extinction of one to ten million years (Thomas, 1990).

Recent human history gives better examples of how to define the viable size of a space colony. When a new population is established by a small number of individuals from a larger population, it's subject to the founder effect, first described by evolutionary biologist Ernst Mayr. The founder effect leads both to loss of genetic variation and genetic divergence from the original population. The sweet spot for a space colony may be the size of a village. John Moore, an anthropologist from the University of Florida, developed simulation software for analyzing the viability of small groups (Carrington, 2002). He suggests the optimum number for a viable long term colony is 160. This number could be reduced with judicious genetic selection to minimize the probability of inbreeding.

If space colonists don't get "new blood" from the home planet, their gene pool will experience genetic drift. Genetic drift is the change in frequency of gene variants or alleles due to random sampling. The effect is larger in smaller populations and it acts to reduce genetic variation, which in turn reduces a population's ability to respond to new selective pressures. This sounds bad, but genetic drift and the founder effect on Earth are major drivers of evolution. They lead to the formation of new species.

Over generations, the colonists will evolve. We can imagine some of the changes that will take place. The lower gravity on Mars will alter the cardiovascular system and reduce the cross–sectional area of load–bearing bones and tendons. There will be accelerated trends seen in human evolution on Earth—toward being taller, and having less body hair, weaker muscles, and smaller teeth. The lack of a varied natural environment would probably lead to weaker immune systems. An additional challenge will be to maintain sensory stimulation as well as intellectual stimulation, to keep the brain sharp (Finney and Jones, 1985). A new species will have evolved if off–Earth humans can no longer mate and produce viable offspring with those who never left Earth. We know this will take a long time because a small group of people went on a one–way trip to the Americas about 14,000 years ago, and when they encountered Europeans 500 years ago, they were still the same species. Some groups in Australia and Papua New Guinea have been mostly isolated for 30,000 years and speciation didn't occur. For colonists on the Moon or Mars the process will be accelerated by the different physical environment and the higher rate of mutations due to cosmic rays. All of this exploration will be in the Solar System; the stars are so distant they will stay beyond reach.

Finally, after hundreds of thousands of years and thousands of generations, when the first off–Earth baby's cry is no more than an ancestral memory, the colonists will have come of age. They will no longer be us. Imagine the colonists live in total isolation and one day we encounter the ancestors of the people who left our planet. They'll speak their own language, have their own culture, and only resemble us partly. For each side, it will be like looking in an eerily distorted mirror.

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