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**Our Future Off Earth**

Professor Christopher Impey

I would like to talk about the future of space travel. I got interested in this topic and decided to write a book on it last year, which was published by Norton, called “*Beyond: Our Future in Space.”* I was driven by a contrast between two things; the fact there seemed to some large scale malaise in the space program coming on for a century since we first went to the moon, with no sign of us returning, the space shuttle retired after the catastrophic of two out of five orbiters, the space station a large unwanted international pork, and a sense that we lost our way in terms of progress in space. But that contrasts with another strain that’s been very visible in the last year or so, the resurgent interest of the private sector and entrepreneurs in getting us into space cheaper, quicker, and faster than ever before. So out of resolving these two things, I realized that there is a lot to talk about in the future of space.

Let me start by giving you a reference for how difficult space travel is, and how large space is- especially if you ever want to leave the solar system. Let’s imagine a little scale model where we set the Earth to about the size of a walnut, that is about a one in ten-millionth model. The moon on this scale would be a pea held at arm's length, and that is our reference for the difficulty of going to the Moon. Those moon shots back in the late 60’s and early 70’s cost the equivalent of 70 billion dollars in current currency rates to send 12 people to set foot on the moon and 24 to visit it. Those are still the only dozen people to ever set foot on another world. Well that is arm’s length, how far away are other targets within the solar system and beyond? On this scale the Sun would be a 3-meter global about a hundred meters away from the Earth, and Neptune, the edge of the solar system, would be another pea-sized object about two kilometers away. So the solar system is vast compared to the distance between the Earth and the Moon, the only distance we’ve traveled with astronauts. On this scale the nearest star is fifty thousand kilometers (50,000 km) away; it would not even be on the Earth in this scale model. Giving a sense of how vast interstellar space is, and how prodigious we would have to advance in order to travel to the stars.

Let me start with some early history, and perhaps motivate the fact that we explore space for a reason that is a little more than pure curiosity. I think that it is built into our genes. If we look at the way humans migrated across the planet after leaving Africa -about fifty or sixty thousand years ago- it is a fascinating trajectory. Genetic maps show how humans migrated across Asia, through Europe, to Australia, and across the Americas. In a striking small amount of time humans migrated across the Bering Strait and the land bridge to Alaska that existed fifteen to eighteen thousand years ago, and then down through the Americas. It took barely four or five thousand years to move from Alaska down to the southern parts of Argentina. That is a phenomenal amount of travel. It always occurs to me that somewhere halfway down that trip they pasted Southern California, the beautiful beaches of Santa Barbara and Santa Monica. Why didn’t they just stay there?

Well, we are driven by curiosity, so I think humans are the only species on the planet that travel such large distances, in a state of still simple hunter-gathers tens of thousands of years ago, for reasons of curiosity, not just for the local food source and not because they need new resources. This alone marks us out from other animals, which do migrate to follow food sources, but not such prodigious distances. There is research that has bolstered this. There is a correlation between a proportion of a varying of a gene called DRD4 and the allele -on one variation of this allele- and the amount of distance that early migratory cultures traveled on the Earth. In other words, the larger the proportion of this allele of a single gene, the larger the migration of early humans. This variation of a gene is also correlated with ADHD and risk taking behavior of various kinds.

We can imagine that this gene would be dysfunctional if it presented itself too large in a human population, but the natural level of this variation of the gene is 10%, and at that level it provides for a few members of the intrepid band willing to take risks to venture into that next valley, to go across that body of water in a flimsy boat. I think we are built to travel and explore. It is built into our genes. Of course, genetics is complex enough that no single gene can explain the curiosity and motivation for humans to travel on earth or beyond, but there does seem to be a genetic component to this activity.

We can go back through the history of space travel. Perhaps we should start with Wan Hu, a minor functionary of the Chinese emperor’s regime in about 1550. He had dreams of space four hundred years ago. At the signal to his servants, forty-seven servants walked forward to his sedan chair made out of bamboo and lit forty-seven rockets attached the bamboo sedan chair. History records that there was a cloud of smoke and fire, and Wan Hu disappeared, perhaps to become the first astronaut. Almost certainty he died a horrible death, but he had dreams of space hundreds of year before it was possible to get there, and fitting in fact that it happened for a Chinese person because their advances in rocketry of course led the whole subject for hundreds of years.

Rocketry really starts in the early 20th century with Robert Goddard. Again from such humble beginnings, it is hard to envision the Atlas Rocket or the Saturn 5 that would carry men to the Moon. Robert Goddard's first rocket launched from his Aunt Effie’s cabbage patch in a frozen part of the Midwest and traveled about a hundred and eighty meters, and that is all. It was a tiny little rocket that would fit in your pocket. But he was the visionary that led the way for future developments in liquid fueled rockets. Other landmarks are maybe less well remembered. The first monkey, a relative of humans, in space was Ms. Baker, a spider monkey who actually lived to the amazing age of forty. In 1959 Ms. Baker went into orbit, survived the trip and lived to a ripe old age. When Ms. Baker eventually died she was buried with military honors and several thousand people attended the funeral. We should be so lucky to have so many people at our funerals.

Of course, in the early part of the space race the Russians set most of the landmarks. There was an enormous geopolitical pissing contest between the United States and the Soviet Union and for the first 10 years of the space race, most of the landmarks were set by the Russians; the first satellite, Sputnik, the first man in space, Yuri Gagarin 1961, the first woman in space, Valentina Tereshkova, the first space walk. The Americans were shamed and chagrined to have lost all these landmarks and a huge space race was set off that of course culminated in the voyages to the Moon. But in a sense the voyages to the Moon were an anomaly; they represented a funding level for NASA that could not possibly be maintained.

A strange side light on the length of time it is since we have been to the Moon, is the fact that when millennials are asked about this, about 1 in 10 suspect that we never actually went to the Moon, that it is a conspiracy, or that it was faked, or they simply do not understand it. They did not realize this. It is as a dim cultural memory to them. I have to show in my classes, evidence that we left experiments on the Moon that still return data, that with telescopes we can see the tracks of the rovers that moved across the Moon. In fact, it is a shame to deny such a magnificent achievement because the Apollo program was the most extraordinary technological feat of the 20th century, involving tens of thousands of people, costing, of course, tens of billions of dollars, and resulting in an almost unimaginable achievement, given the beginning of the space progress just ten years earlier.

So we have gone into space. We have done it. We know it is hard, and the question is “When will we go back?” or “How will we go back?” I think that for perspective we should remember that the space age is only 55 or 60 years old, and has mostly been the activating of two countries driven by military or geopolitical motives. Less than six hundred have ever been in orbit, and only a dozen have set foot on another world. Space travel is exciting, but it is also very dangerous, and for perspective we should just remember that this is a young activity, still in its early phase.  The malaise of course is represented in the American Space Program by the retirement of the shuttle, which at the time of its retirement was a 40-year-old technology where two of the five orbiters were lost, a catastrophic failure rate of 1 in 50, and of course the death of all astronauts on board in both cases. Years before the shuttle was retired the military gave up on it and built their own launch capability, and the telecom industry uses rockets launched from Europe and China. Progress on the successor to the shuttle in the United States has been slow and halting.

Meanwhile, the other large international project is the Space Station. It was supposed to have cost 8 billion dollars back in 1984. At the current rate it’s heading for 120 billion dollars, and yet has few users amongst the industry and science clients who were supposed to flock to it, although, it is a useful place for experimentation on technology for deep space. These two long running, and very expensive, activities in space barely take us into earth orbit, not beyond. So we have a cloudy vision for the future of space. Of course it’s an ignominy for the United States in particular to be looking at more than five years when America cannot get an astronaut in orbit without help from the Russians. Now you may have noticed that the Americans and the Russians are not getting on that well right now.

Some perspective is provided by the budget for NASA in terms of the American Space Program. The federal budget is approaching four trillion dollars. NASA lives in a tiny part of this budget vying for funds with Social Security and veterans’ benefits, and it does not tend to do too well. At it historical peak in the mid-1960s NASA consumed four and half percent of the federal budget. That was an unsustainable level of expenditure and it fell rapidly. You may recall that the last three Apollo Missions were canceled, and it fell back down to 1% of the budget by the early 1970s. Since then it has continued its decline to half a percent of the federal budget. So NASA has indeed been starved for funds. Although its budget is $18 million, that doesn’t buy very much in the difficult and expensive activity of space travel. Of course, the other problem for NASA is that it is often in the news, often for the wrong reasons. The public tends to remember only when something blew up, or there was a disaster, or when NASA needs money, not necessarily when a major discovery was made or something cool was done in space.

Meanwhile objects in the rearview mirror may be closer than they appear. China is developing a very powerful space program, from scratch, and they have accelerated their activity to the level where they have dozens of launches a year. They have already had their first human spaceflight in 2003, their first lunar orbiter in 2007, and they started to set up a space station start in 2011. They have current goals that include a lunar base, men on Mars, and men on the Moon, and they are spending money on their space program at a growing rate of 8 to 10% a year, mirroring the growth rate of their economy as a whole, and that could be contrasted with NASA’s stagnant budget. So perhaps a new geopolitical space race is brewing between the United States and China. And there is tension there because while NASA was established in 1959 with Eisenhower making a very clear separation between NASA and the military sector, so NASA is truly a civilian space agency, in China space activity is twinned with military activity. It is a very secretive activity where we have to guess what their true intentions are. There clearly is concern about the ‘weaponization’ of space and I think that concern is justified.

A more exciting part of this picture is the private sector. Space tourism started small and very expensive when billionaire Dennis Tito paid $20 million to ride a Russian Soyuz spacecraft for a week's vacation on space station. There have now been seven space tourists paying out large amounts of money for that experience. Charles Simonyi, the investor, went twice and space walked the second time, spending a cool $35 million for his adventure. Well, these are tiny numbers of space tourists. Perhaps the more significant activity is the X prize. Inspired by the $25000 prize won by Charles Lindbergh in 1927 for crossing an ocean in a small biplane. Burt Rutan won the $10 million X prize for a repeated sub-orbital flight reaching 100 kilometers, the formal definition of space. This prize, of course, did not begin to cover the cost of development of those spacecraft, but the point is of course the spurs of a new activity.

Google has a moon prize now for a rover that can go to the Moon, travel 500 meters, and send back data, and universities and individual companies are now competing for that prize. So the idea of a challenge prize to spur activity and competition in space is very successful. Meanwhile, billionaire and entrepreneur Richard Branson of the Virgin Group partnered with Burt Rutan, probably the best aircraft and space designer of the 20th century, to form a spaceship company. Virgin Galactic, of course, has some ambitious plans, but there are 12 or 13 other space organizations worldwide that are operating for the same goals. There are setbacks. Just a year or so ago SpaceShipTwo had a disaster, and so Virgin Galactic was setback with the death of a copilot and the near death of the pilot, but they plan to have paying flights starting perhaps in late 2017. Tickets at the moment are a quarter of a million dollars, so start saving. They already have $40 million of deposits, and over 20,000 expressions of interest. I also know that when SpaceShipTwo was lost, Branson issued all the people who put down deposits their money back, no questions asked. He had very few takers. Many of the people who want to do these short zero gravity suborbital flights are fully aware of the risks and willing to take those risks.

Notice that there are almost 2000 billionaires in the world and growing, so entrepreneurs like Richard Branson are the tip of an iceberg of potentially moderately young investors and rich people who could fund a private space activity. Some of these names are well known, like Richard Branson, others less well known. Peter Diamandis was the founder of the X prize and is an entrepreneur, Elon Musk is well-known in the United States particularly for his development of the tesla car and for his SpaceX company, and the darkhorse in this perhaps is Jeff Bezos the chairman of Amazon, founder of the Blue Origin company, which is competing with Elon Musk’s to develop a reusable orbital vehicle; both have had recent successes. So the plans are for a well-developed vehicle to take people into space to orbit earth for moderate amounts of money, far less than the $10-$20 million the first space tourists paid.

In the UK, Reaction Engines are developing a reusable space vehicle that is air breathing at low altitudes and then goes to five times the speed of sound with rockets taking it to zero gravity. So there is a widespread international activity to develop reusable space vehicles, it is the reusability that will break the cost curve and bring this activity into the realm where perhaps middle-class people can afford it. There is also a spaceport planned in the UK, the final location not yet decided, and there is heavy activity in New Mexico where a spaceport is underway that Virgin Galactic and other private space companies are using. So the groundwork is being set for a new activity, space travel. We know that space travel is hard. The brutal reality behind space travel is the rocket equation, which says what the final velocity of a rocket will be in terms of its fuel and total mass. This unfortunate curve is what said the Apollo missions would be 90% fuel; so huge a rocket was needed to launch a tiny payload into orbit. There is little to get around the rocket equation when you are stuck with using chemical fuel and its low efficiency, but the way the entrepreneurs are doing this is by using modern lighter materials, and in particular by not jettisoning any part of the spacecraft, and re-landing it and therefore reusing the entire entity, which is quite different from the Apollo model, or the space shuttle model.

Branson, Musk and Bezos all plan to reduce the cost per kilogram to earth orbit by an order of magnitude from the current level. At that point space travel will come down below the level of 50 or a hundred thousand dollars a head, and a significant number of people will be willing to do it. Space travel is dangerous and people will die, but we should remember that the model for this is a commercial aviation industry. Since the 1930s the fatality rate per flight in civil aviation has declined by a factor of 100. Air travel is incredibly safe now, and high-risk is usually accepted in the pioneer in phase of activity, as long as there is a viable business model. So we can see that there are plenty of investment possibilities here. The collective wealth of the worlds nearly 2000 billionaires is $7 trillion. That, of course, vastly eclipses the budgets of NASA and all the other space agencies around the world. So if the private sector wants to take this on, they can.

The economic model is interesting too. I teach large classes where I ask my millennials what they would spend for a once-in-a-lifetime trip, perhaps three days in zero gravity, assuming that it has become moderately safe. I can take these numbers and project what the income of space travel would be given their median salary. For the 30 million college graduates in United States, the projected yield, if the price per kilo lowers by a factor of five, which is certainly viable given current investment and current technology, the yield would be $20 billion a year of revenues for the space tourism industry. That is an interesting number because it completely matches what Hollywood gets in a mixture of ticket sales and DVD sales, so we can analogize between space travel and entertainment. I trolled Wikipedia for another set of data to look at the average price of a space launch compared to the average cost of a movie, and the analogy becomes even closer because back in the 1960s and 70s the average space mission was very expensive, hundreds or millions of dollars, the average movie cost perhaps a few million dollars. But those two curves actually crossed a few years ago where the average movie, indeed, costs as much as the average space mission; space missions have gotten cheaper and movies more expensive. Perhaps the best landmark of this is a comparison between “Avatar”, a movie about life on an exomoon, and the Kepler spacecraft. Both of these activities cost about $400 million dollars, a large amount of money. So for just under half a billion dollars you can get a movie about life on other worlds, a very fine movie with a good director, James Cameron, or you can have the Kepler mission, which has actually found, as a scientific experiment, hundreds of earthlike worlds, they cost the same. To me as a scientist, that makes the Kepler mission seem like a good deal.

Meanwhile, another revolution is brewing, based on the miniaturization of technology and electronics in particular. There is a technology called the “cubesat,” which is a standardized 10 centimeter cube into which are put all the components of what used to be large satellites, perhaps the size of a car. These modular elements can be combined in a launch so that the unit cost for one cubesat is very small. The number of cubesats has grown from a handful or a dozen five years ago, to nearly 200 last year. These cubesats are used for all sorts of means to look down at the Earth and do remote sensing and monitoring, but they have dramatically lowered the bar to achieve earth orbit. Cubesats are being put into space by individual citizens, or student groups, or University Departments; no longer do you have to be a whole country or a big company to do this. There is a thing called a “sprite,” which is a small spacecraft, which has an antenna, a microcontroller, a radio transmitter, and small solar cells, and it will fit in the palm of your hand comfortably, and weighs just 100 grams.

To get the big picture on this, I want to extend my analogy to the history of the Internet. The Internet essentially had four phases, there was the Pioneering phase where visionaries like JR Licklider, a name not familiar to most people. In 1960, Licklider wrote a research paper envisaging wireless Internet, data in the cloud, everything we live with now. That’s hard to imagine him seeing this in 1960 when the average computer was the size of a small house. That moved into the incubation of the Internet by the military-industrial complex in the United States mostly, with DARPA and the RAND Corporation, at a time in the 70s when the only people that email worked at research institutes or worked within the military. Gradually this migrated into the research arena with the famous development of the browser by Tim Berners Lee at CERN, and the development of the modern Internet that we know. But the real transition, the Big Bang if you like, of the Internet development happened in 1995, that was here the word Internet was actually coined. That was the year a small company called Amazon was founded by two graduate students out of Stanford, and that is the year that commercial Internet use started.

That is barely 20 years ago, but it is hard to measure how far we have come because the Internet of the commercial world is valued at about a trillion dollars a year and it dwarfs university and government investment in the Internet. But that investment still drives the cutting edge of the Internet, so it is a mixed model where both things happen at once. If we turn to space travel we see the same thing, there was the pioneering phase of Goddard, there was the incubation by the military in the United States through Wernher Von Braun who was secreted back to the United States, his Nazi past sanitized, to become the architect of the Apollo program. Then eventually space travel moved into the R&D Arena with the development of the space shuttle and other international projects through NASA and ESA, and then finally we have the commercial phase. So I do not know what year would be analogous to 1995 with the Internet, perhaps it is this year or next year, but I do believe in 20 years we will look back and see a commercial sector that has grown so fast and become so large that it dwarfs the other types of investment in space travel. I think space travel is literally set to take off.

So what is on the horizon? Well we can imagine that suborbital travel by Virgin Galactic will become fairly common after the teething phase is over. We can imagine that orbital travel will start to become more common. Bigelow Industries is developing space hotels, so we can imagine that people want to take vacations in space, initially very rich people, but eventually maybe not so rich people. The Google Lunar X prize will spur activity of exploration on other worlds. Perhaps beyond the Moon, to Mars, using miniaturized robotic technology. These technologies are advancing very rapidly, and much of this development will happen in the private sector. Space will get commercialized and that may not be a good thing. As an astronomer the thing I dread, of course, is advertising in space, and huge billboards, and neon signs, and the Moon being littered with commercial trash, but this may happen. It is very hard to regulate it. Remember that almost no modern space faring country has signed the Treaty of the Moon. Although no one can own the Moon or Mars, or the other celestial bodies, enforcement of these treaties, even if they have been signed, is extremely weak.

Meanwhile, there are other possibilities for the next few decades. One is a “stairway to heaven,” the so called space elevator. When Arthur C. Clarke, who envisaged the space elevator long ago, was asked when space elevators would become a reality, he said, “50 years after people stop laughing.” What is a space elevator? It is a cable tethered on the Earth that is splayed out into space to the point where the centrifugal force of the Earth balances the weight of the cable, so it literally hangs there like an Indian rope trick. That means an extremely long cable that has to be incredibly strong to sustain its own weight. Once that cable is assembled, however, going into earth orbit becomes almost trivial, using cars that just ride up and down the elevator using solar power, obviating the need for rockets, and chemical energy, and the enormous expense of the rocket equation, so a space elevator is an admirable goal. If built by consortium of companies and countries, it is a feasible project. At the moment there is no material with the tensile strength to construct a space elevator on the Earth. However, current technologies are sufficient to put a space elevator on the Moon with its 1/6th gravity. Why go to the Moon? Because with a space elevator on the Moon the infrastructure could be built on the Moon and then transported into zero gravity fairly easily, and cheaply, and then the solar system becomes your playground. So I think a space elevator is going to happen within 10 to 15 years because there is no technological obstacle and the commercial activity that it unleashes could be substantial.

The other activity that has been in the news, that has a little more of a gleam in the eye, is mining asteroids. Remember, historically the economic progress on our planet has been fueled by access to cheap metals and minerals. Aluminum is a classic historical example because over the last hundred years it has essentially become so cheap as to be free. At the moment a lot of industries are limited by things like rare earth and platinum group metals. There are over a hundred near-Earth asteroids over 500 meters in diameter. A single one of those harnessed into an earth-moon orbit could provide platinum group metals worth about two trillion dollars. Also mining these asteroids could provide water for all conceivable space travel versus the current cost of $20,000 a litre shipping it from the earth using rockets. Water of course can provide for a habitat, for people, and the water can be separated for oxygen to breath, and then hydrogen to make rocket fuel. So mining asteroids is a definite option and there are several enterprises that are playing out 10 and 20 and 30-year strategies for doing that.

Will we ever leave the Earth? That is really hard to say. If I try to look beyond the horizon it is almost impossible to make predictions. Since I have made analogies with technology and computers, let me recall some of the dangerous predictions made about computers. There is Thomas Watson the chairman of IBM in 1943 saying, “I think there’s a world market for maybe 5 computers.” There is the Popular Mechanics magazine in the US saying in 1949, “Computers in the future may weigh less than 1.5 tons, and then there is Ken Olsen, the CEO of Digital Equipment Corporation, in 1977 saying, “There’s no reason anyone would want a home computer.” Even Bill Gates has been caught by this, saying 20 years ago he couldn’t imagine anyone with a need for 64K of RAM. It is very hard in exponentially growing industry to project the future. Space travel is limited by laws of physics, so it is not at an exponential growth phase, but at the miniaturization end there’s definitely exponential progress due to Moore’s law.

The problem of getting far beyond the Earth is physics again because the distances are so large that current speeds are so slow. In relativity, physics imposes a limitation. As light speed is approached, energy from propulsion simply goes into increased mass and inertia rather than increased speeds. So the energy costs of exhilarating any object, even a tiny one, above 10% of the velocity of light are formidable. The fastest spacecraft we have ever built would take tens of thousands of years to reach the nearest stars, since they can only travel at a tenth of a percent of the speed of light and this is simply too slow for any realistic interstellar transport. The real problem is that our fuels aren’t good enough. Essentially everything in the space program, even by the modern era of space entrepreneurs, uses chemical fuel, and chemical fuel is hundreds of thousands or millions of times less efficient than nuclear fuel, by fission or fusion. We simply do not have a viable technology to use these much more efficient mechanisms, and a lot of R&D has simply not been done on this. An alternative to carrying the fuel is to gather it in space itself. The space between planets does have a thin gruel of hydrogen that could be harnessed fused as a propellant, but there is no viable technology to do that, so at the moment we’re kind of stuck.

Notice, there is a new project in town that is envisioning us going beyond the planets to stars. Breakthrough Starshot, which has an impressive Board of Directors composed of Yuri Milner, Russian entrepreneur who just year or so ago spent $100 million on SETI, the Search for Extraterrestrial Intelligence. He has now devoted $100 million on this new project. The other members of the board are Stephen Hawking and Mark Zuckerberg, the Facebook founder and CEO. These three people and their technical team are envisaging using tiny miniaturized satellites, or nanobots, powered by solar sails to travel to the nearby star Alpha Centauri, and do so in a few decades. It is an incredibly ambitious project, adventurous, and probably facing many technological hurdles because what has to be done is that enormous kilometer sized array of pulsed lasers has to provide the motive power into orbit to accelerate these tiny bots to about 20% of the speed of light to make that journey. These first ideas have just been announced and it will be interesting to see how they play out.

Some things are essentially off the table. One idea that has been around for decades is the idea of terraforming Mars, not only setting up a base there and living in a small habitat, but actually changing the entire planet to make it viable for human habitation. Modest scale living on the moon and Mars is entirely feasible, and could be done within a few decades. The Martian and lunar soil can be mined for oxygen, which can be used to make rocket fuel and to breath. There is about 1 liter of water in every cubic meter of the Martian and lunar regolith, which is certainly sufficient for agriculture, and the regolith or soil itself can be fused by fairly simple processes to make slump block and a hardened silo around the inhabitants, protecting them from cosmic rays. These are very small habitats, transforming Mars entirely is an entirely different matter. That would involve building up the atmosphere by creating a greenhouse effect, therefore, increasing the carbon dioxide in an accelerating way as to release the underground water content, then seeding the planet with extremophile microbes that would gradually oxygenate the atmosphere and thicken it further, and heat up further, and then finally having some photosynthetic microbes, and plants, and making it habitable for humans. The minimum price tag and time scale on such a project, which has been developed in terms of NASA studies, is about 300 years and a few trillion dollars, so I do not think we will terraform Mars any time soon. If we want to have a place to live in the near future it is going to have to be the Earth. We have to take care of our planet.

Let me end by making some cautious predictions for the next hundred years. I think we will find the nearest neighbour earth within about 10 years. Astrobiology and the search for exoplanets is moving so far that we will be able to find whether, say Alpha Centauri has an earthlike planet, and we get lucky that it is in our nearest stellar system, therefore, providing a compelling target for projects like Breakthrough Starshot, or whether the nearest earth is much further away. I think by 2025 we might develop the rudiments of key ingredients for interstellar travel, suspended animation. Medical experiments using pigs and dogs, the closest mammal analogues to humans, have shown that body fluids can be replaced, and these animals can be put into a wait-state for up to several days with a moderate success rate in bring them back. If humans are ever going to travel far into the solar system or beyond they will have to go into suspended animation, and I think that technology will evolve fairly rapidly. I’m going to predict that the Chinese will be the first to make a moon base in the year 2030. The space race we are witnessing now is going to let them into the lead very quickly because of the shear investment they are making, and the national pride that is associated with space travel for that country, which indeed by then will be the world’s largest economy. I’ll predict that Virgin Galactic, SpaceX, and Blue Origins will succeed in their efforts to make commercial spaceflight economical to Earth orbit, so by 2035 I think we will have seen a thousand space tourists.

By 2040 I imagine that the private sector will not only be doing their own innovations, but will be dusting off some of the plans NASA has had for decades that it does not have the money to fund. I imagine Virgin Europa, the dissent of the next chairman of Virgin, after Richard Branson, investing in a mission to Europa to melt through the ice pack, release a hydrobot into the underground water, and look for life there. Perhaps that will be the first detection of life beyond Earth. I imagine by 2045 the first baby will be born off-earth, in orbit. That is an event as epochal as us leaving Africa 50,000 years ago, a major transition in human development and human history. Mars will be a tougher nut to crack, and I do not think it will be until 2050 that we have a viable, sustainable Mars colony. In 2055, I predict the Google Botnet. Google and its continuing efforts to dominate the world of information and data will send fleets of nanobots out into the interplanetary space to explore the moons and planets and send back data, and, of course, the private sector will do it much more efficiently and cheaper than NASA can. And then I predict that by 2060 the Breakthrough Starshot, or a similar project, will succeed and we will send a first miniaturized set of probes to the Alpha Centauri system. Perhaps by 2080, the next stage will happen where the probes that are sent out into the solar system can replicate, or mine materials on asteroids to make more versions of themselves, which then will propagate exponentially. This self-sustaining propagation will proliferate our probes out into the nearby regions of space, sending back the information to Earth at light speed. These are called Von Neumann probes after a pioneer computer science in the early to mid-20th century.

And by 2100 I predict that we have the first rudiments of teleportation, a truly visionary Star Trek technology where information can be transmitted instantaneously or at the speed of light across large distances. At the moment teleportation is not prohibited by the laws of physics, but the practicalities of having entangled quantum states involving large amounts of quantum information are beyond our grasp, but perhaps in 100 years this will not be the case. Either way within 100 years, even if travel to the stars remains just beyond reach, I predict that we will have mastery of the Solar System, and that will be an amazing achievement. Let me leave you with evocative images of humans living in and exploring the Solar System, set to the words of Carl Sagan. Rather than the end of the space program, I think this is just the end of the beginning. Thank you.

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