The Future of Space Exploration and Technology

Lord Martin Rees

I'll start with a flashback to Isaac Newton. He must have thought about space travel. Indeed, there is a famous picture, in the English edition of his *Principia*, which depicts the trajectory of cannon balls being fired from a mountaintop. If they are fired fast enough, their paths curve downward no more sharply than the Earth's surface curves away underneath them: the cannon-balls go into orbit. This is still the neatest way to teach the concept of orbital flight.

Newton could calculate that, for a cannon-ball to achieve an orbital trajectory, its speed must be 25000 km/hour. But that speed wasn't achieved until 1957 with the launch of Sputnik 1. Only twelve further years elapsed between the historic 'one small step for a man' on the lunar surface in 1969. I never look at the Moon without being reminded of Neil Armstrong and Buzz Aldrin. In retrospect, when we realize the primitive computing support available at that time, and the untested equipment, this exploit seems even more heroic and historic – especially as the Apollo programme remains, a half-century later, as the high point of human ventures into space. This programme was conceived as a 'space race' against the Russians. Once that race was won, there was no motive for continuing massive expenditure. In the 1960s NASA absorbed more than 4% of the US federal budget. The figure today is 0.6%. Had the higher momentum been maintained, there would surely be footprints on Mars by now: that's what our generation expected.

It's nearly 45 years since Apollo 17, the last lunar mission, returned to Earth. Today's young people know the Americans landed men on the Moon. They know the Egyptians built pyramids. But these both seem ancient history, motivated by almost equally bizarre national goals.

Hundreds more have ventured into space in the ensuing decades – but, anticlimactically, they have done no more than circle the Earth in a space station. The International Space Station (ISS) was probably the most expensive artifact ever constructed. Its cost, plus that of the Shuttles whose main purpose was to service it (though they have now been decommissioned), ran well into twelve figures. The scientific and technical payoff hasn't been negligible, but it's been immensely less cost-effective than unmanned missions. Nor are these voyages inspiring in the way that the heroic pioneering Russian and US space exploits undoubtedly were. The ISS only makes news when something goes wrong: when the plumbing or electronics fail – or when astronauts perform 'stunts', such as the Canadian Chris Hadfield's guitar-playing and singing.

Despite the languishing of manned spaceflight, space technology has of course burgeoned: we depend routinely on orbiting satellites for communication, sat-nav, environmental monitoring, surveillance, and weather forecasting. And many nations – not just the superpowers – undertake space projects. Much of this work involves spacecraft which, though unmanned, are expensive and elaborate. (Indeed the GPS and Galileo systems on which sat-nav depends need to be so precise that the gravitational corrections in clock rates due to general relativity must be taken into account: this is the first technological application of Einstein's general relativity.)

But dramatic advances in miniaturisation and computing power have enabled the manufacture of cheaper standardized spacecraft. For instance, the San Francisco-based company 'Planet' has launched 70 shoebox-sized spacecraft as payload on a single Indian rocket. Their collective purpose is to give global coverage of the Earth's surface, albeit at not-specially-sharp resolution. The mantra (with only slight exaggeration) is to observe every tree in the world every day. The system is optimized to observe changing land-use, construction projects, and so forth. There is a market for 'cubesats' only 10 centimetres in size. And even smaller wafer-thin satellites can now be deployed, basically using the same amazing technology that has emerged from the high investment in smartphones.

Space telescopes have been hugely important for astronomy. Orbiting far above the blurring and absorptive effects of Earth's atmosphere, they have beamed back data from the remotest parts of the cosmos, in wavebands such as infrared, UV, x-rays and gamma rays which can't be observed from the ground. They have revealed new cosmic phenomena, and probed with high precision the 'afterglow of creation ' – the microwave radiation pervading all space whose properties hold clues to the very beginning , when the entire observable cosmos was squeezed to microscopic size.

Of more immediate public appeal – because more readily comprehensible – are the data from spacecraft that have journeyed to all the planets of our Solar System. NASA's 'New Horizons' probe beamed back amazing pictures from Pluto, 10,000 times further away than the Moon. And ESA's Rosetta has landed a robot on a comet. These spacecraft took five years to design and build, and then 10 years journeying to their remote targets; so they embody old-fashioned technology. And Cassini is even more of an antique: more than 20 years elapsed between its launch and its final plunge into Saturn in late 2017.

We're aware how mobile phones have changed in the last 15-20 years – so imagine how much more sophisticated today's follow-ups to these missions could be.

During this century, the entire Solar System – planets, moons and asteroids – will be explored and mapped by flotillas of tiny robotic craft, interacting with each other like a flock of birds. Giant robotic fabricators will be able to construct, in space, huge solar-energy collectors and other artifacts. The Hubble Telescope's successors, with huge gossamer-thin mirrors assembled under zero gravity, will further expand our vision of stars, galaxies and the wider cosmos. The next step would be space mining and fabrication. (And fabrication in space will be a better use of materials mined from asteroids than bringing them back to Earth).

It's robots, and not humans, that will build giant structures in space. And sophisticated robots will explore the outer planets: they will have to utilize the techniques of deep learning and AI to make autonomous decisions – the travel time for a radio signal to the outer planets is measured in hours or even days, so there's no possibility of direct control from Earth. These robots won't be humanoid in size and shape. Humans are adapted to the Earth's environment. Something more spider-like would be better suited to the weaker gravity of Pluto or the asteroids

But will these endeavours offer a role for humans? There's no denying that NASA's 'Curiosity', a vehicle the size of a small car that has since 2011 been trundling across Martian craters, may miss startling discoveries that no human geologist could overlook. But machine learning is advancing fast, as is sensor technology; whereas the cost gap between manned and unmanned missions remains huge. The practical need for manned spaceflight gets ever weaker with each advance in robots and miniaturization.

Nonetheless I hope some people now living will walk on Mars – as an adventure, and as a step towards the stars. But NASA or ESA will confront political obstacles in achieving this goal within a feasible budget.

NASA's manned programme, ever since Apollo, has been impeded by public and political pressure into being too risk-averse. The Space Shuttle failed twice in more than 130 launches. Astronauts or test pilots would willingly accept this risk level, but the Shuttle had, unwisely, been promoted as a safe vehicle for civilians. So each failure caused a national trauma and was followed by a hiatus while costly efforts were made (with very limited effect) to reduce the risk still further.

China has the resources, the dirigiste government, and maybe the willingness to undertake an Apollo-style programme. If it wanted to assert its super-power status by a 'space spectacular' and to proclaim parity, China would need to leapfrog, rather than just re-run, what the US had achieved 50 years earlier. A permanently manned lunar base would be one option. But a clearer-cut 'great leap forward' would involve footprints on Mars, not just on the Moon.

But, leaving aside the Chinese, the future of manned spaceflight lies with privately-funded adventurers, prepared to participate in a cut-price programme far riskier than NASA or ESA would countenance. That's why these organizations should share expertise and collaborate with outfits like Space X, led by Elon Musk (who also builds Tesla electric cars) or the rival effort, Blue Origin, bankrolled by Jeff Bezos, founder of Amazon. Their spacecraft have docked with the Space Station and hope soon to offer orbital flights to paying customers. These companies – bringing a Silicon Valley culture into a domain long-dominated by NASA and a few aerospace conglomerates – have shown it's possible to recover and reuse the launch-rocket's first stage – presaging real cost-saving. (They have advanced the techniques of rocketry far faster than NASA or ESA has done – these governmental organizations will in future have a more limited role more akin to an airport than to an airline).

Indeed, it would be best to let inspirationally-led private companies 'front' all the manned missions. These private ventures can tolerate higher risks than a western government could impose on publicly-funded civilians; they can thereby cut costs compared to NASA (or ESA). There would, nonetheless, be many volunteers – accepting high risks and perhaps even 'one-way tickets' – driven by the same motives as early explorers, mountaineers, and the like. (The phrase 'space tourism' should be avoided. It lulls people into believing that such ventures are routine and low-risk. And if that's the perception, the inevitable accidents will be as traumatic as those of the Space Shuttle were. Instead, these cut-price ventures must be 'sold' as dangerous sports, or intrepid exploration).

But there could be technical breakthroughs in the longer-term. The most crucial impediment to space flight, even in Earth's orbit and still more for those venturing further, stems from the intrinsic inefficiency of chemical fuel, and the consequent requirement to carry a weight of fuel far exceeding that of the payload. (It's interesting to note, incidentally that this is a generic constrain, based on fundamental chemistry, on any organic intelligence that had evolved on another planet. If a planet's gravity is strong enough to retain an atmosphere, at a temperature where water doesn't freeze and metabolic reactions aren't too slow, the energy required to lift a molecule from it will require more than one molecule of chemical fuel).

So long as we remain dependent on chemical fuels, interplanetary travel will remain a challenge. A space elevator would help. But nuclear power could be transformative. By allowing much higher in-course speeds, it would drastically cut the transit times to Mars or the asteroids (reducing not only astronauts' boredom, but their exposure to damaging radiation). And lasers on the ground can accelerate small spaceprobes to high speeds.

By 2100 thrill-seekers in the mould of (say) Felix Baumgartner, who broke the sound barrier in free fall from a high-altitude balloon, may have established 'bases' independent from the Earth – on Mars, or maybe on asteroids. Elon Musk of Space-X (born in 1971) says he wants to die on Mars – but not on impact.

But don't ever expect mass emigration from Earth. And here I disagree strongly with Elon Musk, and with my colleague Stephen Hawking, who promote rapid build-up of large-scale Martian communities. I think it's a dangerous delusion to claim that space offers an escape from Earth's problems. We've got to solve them here. Coping with climate change is a doddle compared to terraforming Mars. Nowhere in our Solar system offers an environment even as clement as the Antarctic or the top of Everest. There's no 'Planet B' for ordinary risk-averse people.

But we (and our progeny here on Earth) should cheer on the brave space adventurers. This is because they will have a pivotal role determining what happens in the 22nd century and beyond – and even spearheading the transition to a post human era.

A century or two from now, there may be small groups of pioneers living independent from the Earth – on Mars or on asteroids. Precisely because space is an inherently hostile environment for humans, these pioneers will have far more incentive than us on Earth to re-design themselves. They'll harness the super-powerful genetic and cyborg technology that will be developed in coming decades. These techniques will be heavily regulated on Earth, but Martian colonists will be far beyond the clutches of the regulators.

Whatever ethical constraints we impose here on the ground, we should surely wish these adventurers good luck in genetically modifying their progeny to adapt to alien environments. This might be the first step towards divergence into a new species: the beginning of the post-human era. And genetic modification would be supplemented by cyborg technology – indeed there may be a transition to fully inorganic intelligences.

So it's these thrill-seeking spacefarers, not those of us comfortably adapted to life on Earth, who will spearhead the post-human era.

Organic humans like us need a planetary surface environment – but if posthumans make the transition to fully inorganic intelligences, they won't need an atmosphere. And then may prefer zero-g, especially for constructing massive artifacts. So it's in deep space – not on Earth, not even on Mars – that non-biological 'brains' may develop powers than humans can't even imagine.

Few doubt that machines will gradually surpass more and more of our distinctively human capabilities – or enhance them via cyborg technology. Disagreements are basically about the timescale – the rate of travel, not the direction of travel. The cautious amongst us envisage timescales of centuries rather than decades for these transformations. Be that as it may, the timescales for technological advance are but an instant compared to the timescales of the Darwinian selection that led to humanity's emergence – and (more relevantly) they are less than a millionth of the vast expanses of cosmic time lying ahead.

So in a cosmic perspective, the present era, dominated by humanity and its artifacts represents a thin sliver between the four billion years of pre-human Darwinian evolution, and the billions of future years of evolution via technological 'intelligent design' – here on Earth and far beyond.