17 Outlook

This final chapter first takes a brief look at some speculative ideas for propulsion that currently lie at or beyond the edge of known physics. I then return to reality and summarize the main challenges of interstellar travel along with the most promising solutions we have considered in this book. I look again at the big picture of what we want to achieve and its ethical implications, and finish by briefly describing some steps that could be taken to get us on our way to the stars.

17.1 The edge of physics

I started this book by saying I would limit the scope to known physics, even if the engineering or financing could be extreme. Let us nonetheless take a brief look at some ideas that operate at the edge of physics, without necessarily violating accepted physical laws. The ideas focus mostly on moving between two points faster than light can, but without contradicting general relativity. Direct faster-than-light travel is not possible within even special relativity, because it would require an infinite amount of energy to get a finite mass up to the speed of light. If it were possible, it would also violate causality by allowing information – or in principle a person – to travel back in time, thereby creating paradoxes such as what happens if you kill your parents before you were born. Some of the ideas below also violate causality.

There are of course descriptions in science fiction or popular culture for faster-than-light travel that simply ignore known physics entirely. But without a replacement theory that can be tested, these descriptions are free to claim anything, so I don't consider them.

While the following ideas are curious, inspiring, and fun, they are at best impractical, at worst speculative, and cannot (yet) be the basis for any serious work on interstellar travel.

17.1.1 Warp drives

Captain Picard commands 'engage' and the Enterprise zips off at faster than the speed of light. Science fiction aside, things called warp drives have been the subject of serious scientific study. A 1994 paper by Miguel Alcubierre showed that within the framework of general relativity, it is in principle possible to distort spacetime around a small bubble, such that this bubble acquires an arbitrarily large velocity relative to an external observer. This is achieved by contracting spacetime in front of the spacecraft and expanding it behind the spacecraft, making it travel to a distant point in an arbitrarily short time. Within its local spacetime the spacecraft does not travel faster than the speed of light. In fact, it does not move at all, and the passengers experience no acceleration.

The drawback of this idea is that it requires a negative energy density to produce the necessary spacetime distortion. Although tiny amounts of negative energy do occur in the

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quantum mechanical Casimir effect, this warp drive needs vast amounts of it. An energy equivalent to the mass of the Sun would be needed to create a bubble about a metre in size. Even if such amounts of negative energy were available, there is no known way to manipulate it to create the required distortion. And even if there were, the spacecraft itself could not control the bubble. This would have to be done from the outside.

Alcubierre's paper nonetheless inspired follow-up work. Alternative warp drive models arising from general relativity have since been suggested. Although these do not overcome the significant practical problems, they have provided a deeper understanding of the concept. Interestingly, there are warp drive solutions for subluminal velocities that require only normal positive energies.

17.1.2 Wormholes

Black holes are sometimes used as convenient plot devices in science fiction stories to take a short cut to a distant star system. The problem with black holes is that (i) all but the most massive black holes induce enormous tidal forces that would rip a spacecraft apart, (ii) observed from the Earth, a spacecraft would take an infinite amount of time to cross the event horizon, and (iii) nothing can escape from the event horizon. This final inconvenience is sometimes countered by invoking a white hole exit at the destination, this being the hypothetical opposite of a black hole. But white holes are unstable, and the exit would seal itself before the spacecraft had a chance to emerge.

Rotating black holes, described by the Kerr metric, in principle provide a route back to flat spacetime, but this route is plagued by singularities and is also unstable. Even if these difficulties could miraculously be solved, these so-called Kerr tunnels lead to causality violations of the you-can-kill-your-parents type.

The wormhole is a solution to the general relativistic field equations that either connects two different universes or two arbitrarily distant points of a single universe. The connection, sometimes called an Einstein–Rosen bridge, suffers from many of the same problems as the black/white hole and Kerr tunnel between them, however, so this type of wormhole (Schwarzschild wormhole) is considered to be non-traversable. One particular difficulty is keeping the wormhole open: the throat of the tunnel expands and contracts (to zero, leading to disconnection) too rapidly to be able to pass through even at the speed of light.

There are, however, solutions of Einstein's equations that overcome the above problems, although we have no idea how to construct such traversable wormholes, or whether the laws of physics even allow them to be constructed. In addition to lower tidal forces and finite travel time (for both the spacecraft and external observers), the wormhole has no horizons, so two-way travel is in principle possible. However, the wormhole would have to be stabilized to perturbations, such as passing a spacecraft through it, and it is not clear whether that is possible. A big remaining problem is that to construct the wormhole, exotic matter with a negative energy density is required (as for the warp drive). Maybe there are quantum mechanical solutions (suggested by the Casimir effect), but until we have a quantum mechanical theory of gravity, we can only speculate.

17.1.3 Other ideas

Dark matter and dark energy appear to be prevalent in the universe, as inferred from their effects on visible matter, yet we have very little idea what they are. Sometimes dark matter

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or dark energy is invoked as a source of propulsion, or of exotic matter, but without having a testable theory of what they are, this remains purely speculative.

Various ideas to use astrophysical objects to provide propulsion have been suggested. These include performing extreme gravity assists around compact binary neutron stars, or deploying light sails or electric sails very close to supernovae or microquasars, where the energy fluxes are extremely large. Although these approaches are physically permitted, we would first have to travel the enormous distances to these exotic objects before we could use them to get anywhere else.

Another idea, familiar from science fiction, involves crossing into additional spatial dimensions beyond the familiar three. The purpose of jumping into this so-called hyperspace is to travel between two points in a time that is less than their light–travel time separation in normal space. Somehow time is not spent, or is reduced, when travelling in the additional dimension(s). String theory motivates the idea of higher dimensions, but without an actual theory of hyperspace we can say nothing about how we would cross into it.

A somewhat different idea for propulsion is that of antigravity. If gravity could be shielded in the way that electromagnetic fields can be, this would make escape from the solar system much easier, requiring much less propellant. An anti-gravitational force would even mean that a spacecraft would be accelerated away from the Sun. But assuming inertial mass remained unaffected, the gravity-free rocket equation would still be a limitation, so antigravity wouldn't be a big help.

Finally, there have been experimental investigations into so-called reactionless drives. These are essentially rockets without propellant, and so defy the law of conservation of momentum. There have been some experimental claims of their existence, but none of these could be reproduced under carefully controlled conditions. Giving up on a concept as fundamental as momentum conservation naturally requires very strong evidence (and might leave us wondering about a lot of phenomena and physical devices that depend on it). But as scientists we should be open to ideas and in particular to experimental evidence that could push the boundaries of known physics. Who knows what may lie beyond the edge?

17.2 Challenges and solutions

At the start of this book, I set down the goal of getting to a nearby star within a human lifetime. One of the biggest challenges is achieving the high velocity of around 10% the speed of light that this implies. It requires phenomenal amounts of energy even for small payloads. To reach this speed we can forget chemical rockets, ion engines, solar sails, and in fact anything else currently in use. Antimatter engines and the Bussard ramjet are physically possible but are so far fetched that we can rule them out for at least the foreseeable future. The two most promising propulsion technologies are fusion rockets and laser-driven sails. Both of these are extremely challenging.

Fusion rockets work either by inducing a series of small fusion explosions and coupling the charged products to the spacecraft via a magnetic field, or by having a sustained fusion reaction that leaks some plasma to act as a high-momentum propellant. Both approaches come with enormous challenges. One of the most promising fusion reactions for propulsion uses helium-3, but this barely exists on the Earth. It would have to be mined from the surface

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of the Moon or from the gas giant planets. Reactions involving only more-readily available isotopes such as deuterium and boron are more demanding to achieve. So far we have not achieved net energy-producing fusion on the Earth. And even for those serious fusion projects in development, their reactors are far too massive to conceive putting them in a spacecraft. Although there has been some research and development on fusion engines that siphon off plasma as propellant, they all remain far from their goal.

Laser-driven sails require very light materials and extremely powerful lasers focused by large telescope arrays. This offers a very different approach to propulsion than fusion engines. As a fusion engine itself (plus its propellant) would be relatively massive, surely tens of tonnes or more, it could carry a relatively massive payload, perhaps tens or hundreds of kilogrammes. Due to limits in laser power, a laser sail, in contrast, is likely to be just a few tens of grammes or less, with a payload of just a few grammes. This severely limits the scientific instruments that can be carried. However, because much of the cost and effort probably goes into building the laser array needed to propel the sail, and because the laser only operates for minutes to hours, many sailcraft could be launched over the course of many months that would collectively fulfil the scientific mission.

There are more requirements to interstellar travel than just propulsion, of course. One is onboard power for instruments and communication. For a fusion engine this may be relatively straightforward to address, as the nuclear reactions could provide electricity too. For a low-mass laser sail, in contrast, onboard power is a serious problem for which there is no obvious solution, as things like RTGs are still far too heavy. One option might be to hibernate the spacecraft for its journey and then use photovoltaic cells powered from the light of the target star during its flyby.

The third major challenge is communication. This is probably better done in the optical than in the radio (ideally in the ultraviolet, but more likely at visual or near-infrared wavelengths). Amazingly, signals from a telescope transmitter a few metres in diameter operating at several watts at the distance of Proxima Cen could be detected by a 30 m telescope on the Earth (or in orbit). But the data rates are extremely small, just a few tens of bits per second, even assuming we can transmit several bits per photon (which has been demonstrated). To scale this up we can either make the transmitter larger or more powerful – difficult given onboard mass limitations – or make the receiver larger, which is comparatively easier. With a hundred 10 m telescopes we could attain data rates of the order of $10\,\mathrm{kb\,s^{-1}}$, and sending data over many years then yields a reasonable data volume. The very large optical array required to propel laser sails could perhaps be repurposed as a receiver, which gives an extra incentive to use this type of propulsion technology. In the 50 years between launch and data reception, astronomers would be overjoyed to use this enormous array for science. It could also be used as part of the mission to study potential target systems, perhaps discovering new planets and helping optimize the science observations.

The time available for collecting data will be very limited for a flyby mission, so a spacecraft that goes into orbit is greatly preferred. A sailcraft has very limited opportunities to decelerate at the target star (the photons from the star reflecting off the sail won't decelerate it much). If the target is a binary or triple star system (as Alpha Cen is), a larger deceleration could be achieved with a combination of stellar photons and gravity assists. Electric and/or magnetic sails potentially give a much larger deceleration, but these are large, massive structures, incompatible with the lightness of a sailcraft. It's hard to see how we could get a fast laser sail into orbit at the destination. A fusion rocket has a big advantage here. By

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taking its propellant with it, it can decelerate significantly. The cost, however, is that the total amount of propellant needed is the square of that required to accelerate it to cruising speed (for a given payload mass). An interstellar orbital mission is a much larger undertaking than a flyby mission.

The fourth major challenge is the survivability of the spacecraft. As it flies at 0.1 c, particles will impact the front of the spacecraft with very high energies. Atoms and ions can be absorbed by a sufficiently thick (around 1 cm) layer of shielding. It therefore makes sense to minimize the cross-sectional area in the direction of travel by making the spacecraft long and thin. Any deployed sails and antennae may be thin enough that they would be perforated. This reduces their effective area, but provided critical components are not hit, it may not inhibit their function. Dust particles are a bigger problem. The larger ones cannot be shielded against and could destroy the spacecraft. The probability of this is low, however. Multiple spacecraft, as foreseen at least with laser sails, nonetheless provide redundancy against total destruction of individual spacecraft.

In summary, I identify the main challenges of fast interstellar travel as propulsion, communication, survivability, and – for low-mass laser sails – onboard power. There are other challenges too, such as navigation, autonomous control, and miniaturizing scientific instruments. These are by no means trivial, but from the current perspective they appear less demanding on the relative scale of things.

17.3 Broader issues of interstellar travel

In this book we have looked at the *physics* of interstellar travel. There are of course wider considerations that need to be addressed before undertaking such a journey. Here I briefly outline a few of the questions we should be asking, but without offering any definitive answers.

Should we undertake interstellar travel? Fast interstellar travel is physically possible. Achieving it will take time, effort, ingenuity, and money. In section 2.1 I outlined some of the possible motivations for pursuing it, first and foremost scientific, but also technological, economic, educational, and cultural. Some people think that we should not invest in technological projects as long as there is poverty and inequality on the Earth, and that we should instead focus on meeting our basic needs first. But what are our basic needs? Their definition has evolved with the development of society, and no doubt varies over the globe. Could we ever agree on when our basic needs have been met? While most people would agree that improving standards of living for everyone is an important task, is it the only thing we should be doing as a civilization? The average human condition has arguably improved with time, and this despite – or perhaps because – we didn't only focus on what we then thought were our basic needs. Learning, vision, and striving for something beyond our grasp surely has as much a place now as it did in the past, and as it will hopefully still have in the future.

No one pretends that interstellar travel is a basic need. But then again neither is the internet, paved roads, or central heating. Money is ultimately a currency for human effort and limited resources, so whether we want to undertake interstellar travel is primarily a question of opportunity cost. What other things would we *not* then do? It is unlikely that striving for interstellar travel would slow progress on medical development or tackling global

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warming, for example. But it might detract resources from similar projects, such as sending people to Mars or building an even bigger particle accelerator. So choices do have to be made and opportunities traded off, but not across the entire spectrum of human desires and activities.

Is interstellar travel ethical? Beside engineering, financial, and political aspects, there are also ethical questions regarding sending a spacecraft to the nearest stars.

Suppose the star system that we target with our spacecraft contains an inhabited planet. Our spacecraft could collide with that planet, potentially contaminating it with terrestrial bacteria or viruses that survive the long cold journey, which then out-compete and wipe out the indigenous life. Is that morally acceptable?

I have only discussed sending robotic spacecraft, yet some people see this merely as a precursor to sending humans. While big generational ships from science fiction novels immediately jump to mind, there are also more modest ideas of sending frozen human embryos or even just DNA sequences, along with the machinery to help them mature upon arrival at a suitable host planet. Is human expansion into the universe morally acceptable? What if the target planet turns out to be inhabited? The reader need not be reminded that humans have a pretty poor ethical record when it comes to colonization. But does some particular form of life have an indefinite and exclusive right to occupy a planet? Some people argue that expansion beyond the Earth is even an obligation, on the grounds that it significantly improves the chance of survival of the human race should we be destroyed on Earth, either through our own actions or by an external agent.

Is interstellar travel dangerous? As with many technologies, there are dangers of dual use. A powerful laser array would be very attractive to a malevolent actor for use as a weapon, for example. Because of this, one could argue that civilized societies should not pursue certain technologies. But one could instead argue that open development and control is a better way of preventing technology from being developed in secret and misused. Furthermore, some seemingly harmless technological development, for example in materials research, may ultimately have dual uses that we cannot anticipate. Does this mean we should close off whole fields of development 'just in case'?

If there is not only life, but intelligent life, in the target star system, how might it interpret a swarm of incoming spacecraft, even if none of these accidentally hit anything? As a reconnaissance prior to an invasion? Anything moving at 10% the speed of light can be interpreted as a weapon. Intelligent life that could observe these could presumably also trace their origin back to our solar system. The multi-hundred-gigawatt narrow-band laser used to propel sails is also a pretty good way of broadcasting our presence. How might aliens react? Movies generally like to portray aliens as hostile – it makes for good action – whereas scientists often like to think they would be other scientists. The truth is that we have no idea and no way of predicting. But we still have to ask ourselves what the consequences could be of sending a spacecraft.

As discussed in the previous chapter, the computers on an uncrewed spacecraft need to be smart for it to operate autonomously. They may even qualify as general AI. Is there a risk that such computers in deep space go rogue, for example using resources of an alien planet to reproduce and then colonize the Galaxy? If our spacecraft met and communicated with intelligent life, might it misrepresent humanity to our detriment?

Should we wait? One thing that some large, technological projects have in common is a progress or incentive trap. If we assume that technology will continue to progress, then

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it might be better to wait to take advantage of this to build a cheaper, better, faster spacecraft in the future. Otherwise we might end up sending a spacecraft now that is overtaken by a faster and more capable one in the future. This, the argument goes, becomes a disincentive to develop anything now, or indeed at any point in the future. In some instances it may well be prudent to wait for specific developments. But as often as not, it is the very act of trying that expedites the developments we need. The incentive trap can also be circumvented if we proceed in smaller steps with precursor missions, as we'll look at in the next section.

Do we need to go so fast? I have talked about 'fast' interstellar travel in this book, with speeds of the order of 0.1 c, because I set the goal of a travel time less than a human lifetime. My choice of this timescale comes from the assumption that society would not be willing or able to pursue a longer mission. Young adults and children who witness the launch could live to see the results sent back, and so would continue to support it in anticipation of this.

But is this single-generational thinking necessary? Maybe it's a symptom of our times. Many medieval cathedrals took multiple human lifetimes to complete, and presumably their architects, builders, and funders often realized this when they started. Although the cathedral analogy should not be stretched, it shows not only that we can run very long-term projects, but also that sometimes this is the only way to achieve remarkable things. Even now, senior scientists initiate – and governments fund – projects they know they will never see the end of. Perhaps not all are motivated by selfish thoughts of their legacy.[1]

A major challenge of interstellar travel is the energy and power needed to get to high velocities. If the travel time can be increased from 50 to 100 or even 200 years, and thus the average velocity lowered to 0.05 c or 0.025 c, some things become disproportionately easier: lasers can have lower power; rockets can use simpler engines or less propellant; damage from interstellar dust particles is reduced; braking with magnetic sails becomes more effective; payload masses can be increased. For travel times of a few hundred years, extremely light solar sails that dive to within a few solar radii of the Sun become an option for propulsion (section 10.7). If we can get used to thinking on longer timescales and being more open to multi-generational projects, this may be a more efficient and effective way to explore nearby stars, despite the longer travel times of individual spacecraft. Each human generation could send out its own spacecraft that will be exploited by a later generation, while simultaneously being able to analyze the results of a mission sent by an earlier generation. Maybe the assumption, embodied in the incentive trap, that we will always want to seek cheaper, better, faster ways of travelling to the stars, is wrong.

17.4 Where do we go from here?

If the technological hurdles to achieving fast interstellar travel appear huge, that's because they are. But to finish something we have to start. Even though there may be some technological breakthroughs which allow us to leap-frog over intermediate steps, we surely need significant amounts of novel research and technology development.

[1] How long a cathedral took to complete depends on your definition of 'complete', plus cathedrals were used before they were finished. Some were also built very quickly: Hagia Sophia in Constantinople was completed in 537 CE after less than six years.

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In terms of rockets, the focus will be on nuclear fusion. Much necessary research on achieving and sustaining net energy-producing fusion is already underway as part of the goal to replace fossil fuels for electricity production. But more specific research will be needed, not least on optimal fuels and on achieving efficient propulsion. Concerning laser sails, the main areas of research are high-power lasers as well as strong ultralight materials that are either highly reflective or are absorbent with a high melting point. Extremely large phase-controlled optical telescope arrays, complete with adaptive optics (if located on the Earth), must also be developed. This goes hand in hand with desirable developments in astronomy.

Beyond propulsion, more research is required on the effect of high-velocity impacts from atoms and dust particles and how to shield spacecraft against them. Mass is a critical factor on spacecraft, so scientific instruments need to be miniaturized and their power consumption reduced. In the realm of communication, we calculated that data from a small spacecraft at Proxima Cen can in principle be received at the Earth. But there need to be significant advances in optical communications technology at the level of individual photons if we are to get anywhere near to the required data rates with acceptably low errors.

We will also need in-flight tests of all technologies. Rather than jumping straight to an interstellar mission, we should first develop one or more precursor missions. These should have significant science goals in their own right in order to gather the support of a wide swathe of the scientific community.

One type of precursor mission is to the outer solar system, to visit Kuiper belt objects, find Oort cloud objects, and explore the heliopause. Multiple spacecraft sent in different directions would allow the shape of the heliopause to be measured directly. They could continue on to directly sample gas and dust in the ISM in order to characterize the particle impacts an interstellar spacecraft will have to survive. Another destination is the solar gravitational lens, starting at 548 au from the Sun in all directions. All of these missions could test not only fast propulsion but also deep space navigation and long-distance communication.

Another type of mission is to use solar sails to rendezvous with long-period comets or interstellar objects. Comets that orbit the Sun on near-parabolic or hyperbolic orbits move rapidly and are only detectable from the Earth shortly before perihelion, leaving little time to launch a spacecraft to intercept them. Solar sailcraft could instead be launched at any time and put on selected parking orbits, or even made to hover if their lightness numbers are high enough. After a target comet has been observed, the sails could then be tilted to follow a fast trajectory to intercept the target. Such sailcraft have some requirements in common with interstellar sailcraft.

A more direct precursor of laser sails – requiring lower- but still very high-power laser arrays on the Earth or in space – is fast interplanetary sailcraft. One example is transport to Mars in a few days, whereby a second laser on Mars would be used to decelerate incoming spacecraft. The laser array required for this could be scaled up over time to propel faster or deeper space missions, and then ultimately used for interstellar missions.

When such precursor missions could start is hard to say, not least because such projects can stand or fall at the whim of other commitments or short-term thinking. It is plausible, though, that some of them could start development by the middle of this century. When the first mission to another star could start depends very much on progress in the technologies I have outlined – or perhaps the arrival of others at the edge of physics – so a prediction is

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almost impossible. If I have to go out on a limb, then I like to think that the first mission could be launched by the end of this century.

Achieving interstellar travel will require imagination, dedication, and patience. Whether or when we achieve it depends ultimately on what we value, and what we are willing to commit. Time will tell. In any case, the journey in this book examining interstellar travel has now come to an end. But the real journey to the stars is only just beginning.

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