Introduction 1

1.1 The interstellar journey starts

On 5 September 1977, just before 09:00 local time, a Titan rocket lifted off from Cape Canaveral in North America. After just two minutes, the rocket was 40 km above the Earth and moving at many times the speed of sound. The launch almost went disastrously wrong at this point because the first stage engines cut off too early. Fortunately, the Centaur upper stage had just enough fuel to compensate. This gave the rocket's payload enough kick to escape Earth's gravity and to send it on its interplanetary mission.

The payload was the Voyager 1 spacecraft; its mission, to explore the outer planets. For the next year and a half, Voyager 1 sped outwards through the solar system, reaching Jupiter in March 1979. Passing within just four Jupiter radii of the planet's surface, it used its cameras, spectrometers, and magnetometers to gather unrivalled information about the planet and its moons as it sped by (figure 1.1).

A carefully planned trajectory allowed the spacecraft to swing around Jupiter and continue on towards Saturn. After another year and a half, in November 1980, it reached the ringed planet and scrutinized it as well as possible in the short time available during the flyby. Moving too fast and having insufficient fuel to slow down, it performed a gravity assist around Saturn to take it past the planet's largest moon, Titan, on its way out.

Moving now at 22 km s^{-1} (4.6 au yr^{-1}) relative to the Sun, Voyager 1 headed off into deep space. Travelling more or less in a straight line, its velocity slowly dropped as it climbed out of the Sun's gravitational well. But it already exceeded the escape velocity of the Sun, and short of an extremely unlikely collision, it was now guaranteed to escape the solar system forever.

For three decades Voyager 1 continued its lonely journey outward, periodically returning information about the gas and dust it encountered, and even taking a snapshot of the distant Earth against the empty blackness of space. Then, in August 2012, when it was 121 au from the Sun, Voyager 1 measured an unremarkable, yet significant, decrease in the ambient particle density. It had crossed the heliopause, what is often taken as the otherwise invisible boundary between the solar system and interstellar space. Voyager 1 had become the first human-made object to leave the solar system.

As of mid 2025, nearly 50 years after its launch, Voyager 1 is 167 au from the Sun and moving at 17 km s^{-1} (3.6 au yr^{-1}). It has just enough energy to operate a couple of instruments and communicate feebly with the Earth. If it were travelling directly towards our nearest star, Proxima Centauri, Voyager 1 would take 77 thousand years to get there. It will instead be hundreds of thousands of years before it gets much closer to any other star. But long before then, its power will fade, its instruments will fail, and we shall never hear from Voyager again.

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Fig. 1.1 Artist's impression of the Voyager spacecraft. Credit: NASA/JPL.

1.2 The dream of travelling to the stars

Sad though the fate of Voyager may seem, it was not only a highly successful interplanetary mission. It has also paved the way for interstellar travel. For hundreds of years, people have dreamed of travelling not just to the Moon or the planets but also to the stars. Humans have walked on the Moon, and for robotic spacecraft interplanetary travel has moved from the realm of science fiction to science fact.

Interstellar travel is a whole new dimension, though. Proxima Cen lies just over 4×10^{13} km from the Sun (4.25 ly, 269 000 au). It is difficult to appreciate distances of this size. If we scale down the universe so that once around the real Earth becomes the distance to Proxima Cen, a scale factor of almost exactly 10^9, then the Earth–Sun distance becomes 150 m, the Sun has a diameter of 1.4 m, and the Earth has a diameter of 1.3 cm. The speed of light is 30 cm s^{-1}. As of mid 2025, Voyager 1 in this scaled-down universe is 25 km from the Sun and moving away from it at 1.5 m per day. It's a long way to the nearest star.

Even with chemical rockets a mind-boggling hundred times larger than those we have now, we could not accelerate spacecraft to more than a few tens of kilometres per second. Getting to Proxima Cen would still take over ten thousand years. Even if humans were gifted with near-infinite patience, any instruments we sent at this speed would be hopelessly outdated by the time they arrived, if they still worked at all, and if civilization was still around to remember it had sent them. If we want to travel to the stars, we have to move faster.

Fortunately, there are technologies on the horizon that could get spacecraft to the nearest stars within a human lifetime. These include fusion propulsion and laser sails. If we could accelerate a spacecraft to 10% the speed of light, we could get to Proxima Cen in just over 40 years. There is no physical barrier to this. Yet the technological challenges are significant, not just in terms of propulsion but also in terms of navigation, onboard power, and communication, to name just some.

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Serious research into interstellar travel has been going on for over half a century. A milestone study was undertaken by the British Interplanetary Society in the 1970s, the result of which was a 50 000-tonne fusion-powered rocket called Daedalus. It aimed to carry a 450-tonne spacecraft to Barnard's Star, the second nearest star to the Sun, in 50 years at an average of 12% the speed of light. More recent studies have focused on lower mass payloads and smaller rockets, and have explored other forms of propulsion. We probably won't leap to the stars in one step, though, and other work has examined precursor missions to explore nearby interstellar space.

1.3 The scope of this book

'It is hard to make predictions, especially about the future.' This maxim surely applies to space travel. Every generation has a tendency to predict future progress as an extension of what it currently has, rather than as something radically different. Futurists in the eighteenth century thought of massive balloons, those in the mid twentieth century of fast atomic spacecraft. Maybe one day we will have warp drives like those in Star Trek, hyperspace as in Star Wars, or wormholes like those in the film Interstellar. But for now, these just remain dreams or theoretical ideas without any hope of becoming reality.

The goal of this book is to examine the physics of getting a real spacecraft to a nearby star with a travel time below a human lifetime. I choose this travel time as being the longest that society would be willing to wait (although I will return to this in the final chapter). Given the range of challenges interstellar travel involves – propulsion, particle shielding, communication, etc. – we will touch on many aspects of physics. This includes classical mechanics, thermodynamics, special relativity, nuclear and particle physics, electromagnetism, optics, and astronomy. We will even look at some fairly extreme applications of physics, such as gigawatt lasers and antimatter propulsion. But we will only consider ideas based on existing proven physics. Things like faster-than-light travel and teleportation are not considered. On the other hand, we will look at solutions that involve some extreme technology that does not yet exist, or that appears absurdly expensive or difficult, but which is nonetheless plausible. It is worth remembering that the computers we have today were physically possible a few generations ago, but were technologically and economically unthinkable at the time.

The other bound on the scope of this book is that we shall only look into sending robotic, uncrewed spacecraft. Human interstellar spaceflight is a fascinating topic, but it involves much beyond physics, such as the biology and psychology of crews. Those interested in sending humans to the stars should nonetheless find most of this book relevant, not only because we will surely send robotic spacecraft first, but also because all of the physical issues still apply to sending humans.

1.4 Types of interstellar mission

When we speak of 'travelling to the stars' we need to be more specific about what we mean. It is useful to split the types of interstellar mission into four categories of increasing difficulty. These are: flyby; orbiter; lander; return. A flyby does exactly that: hardly slowing down, if at

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all, at the destination. An orbiter, in contrast, must almost completely decelerate to get into an orbit around the target star or one of its planets. As we shall see in later chapters, this requires considerably more rocket propellant or – in the case of sailcraft – an elaborate system for braking against the interstellar medium. A lander mission not only requires the spacecraft, or a probe deployed from it, to rendezvous. It must also land on the surface of a body in the star system. This requires an even higher level of autonomy than the first two scenarios. The final mission type is designed to return to Earth, carrying not only data but perhaps also physical samples, maybe even ones taken from a lander. A return mission requires the spacecraft to decelerate at the star, accelerate to return, and then decelerate back at the Earth. This requires considerably more energy or propellant than even an orbiter or lander, and makes the whole mission significantly more difficult.

As a spacecraft travelling at 10% the speed of light would travel 1 au in a little over an hour, a single flyby mission would gather far fewer data than a spacecraft that goes into orbit and could operate for many years. Even though a fast flyby could spend a long period of time sending its data back to Earth, an orbiter is highly preferred. But given how difficult any interstellar mission will be, a flyby seems the more likely choice for the first mission.

1.5 Units used in this book

This book covers a range of topics, so we will need a range of physical units.

In general I use SI units and multiples thereof, such as GW and μm. When discussing electromagnetism, I use SI units and not the still widespread cgs units, which can involve differences of factors of 4π, ϵ_0, and μ_0. I use the symbol 'g' for grammes and 't' for tonnes.

The main exception to the use of SI units is conventional units in astronomy, in particular for the large distances involved. Here I use the astronomical unit (au $= 1.496 \times 10^{11}$ m), the light year (ly $= 63241$ au), and occasionally the parsec (pc $= 3.262$ ly). The light year is rarely used by astronomers, but it is more convenient than the parsec in the context of travel at relativistic speeds. I also use units scaled to the Sun (subscript $\odot$), Jupiter (subscript Jup), and Earth (subscript $\oplus$) for quantities such as luminosity (e.g. $L_\odot$), mass (e.g. M_{Jup}), or radius (e.g. $R_\oplus$). It may be useful to know that $M_\odot = 1048\,M_{Jup}$, $M_{Jup} = 318\,M_\oplus$, $R_\odot = 9.7\,R_{Jup}$, and $R_{Jup} = 11.2\,R_\oplus$ (using equatorial radii).

For angles I use both radians and degrees, depending on context, as well arcseconds ($''$), milliarcseconds (mas), and microarcseconds (μas) as is conventional in astronomy. The conversions are $1^\circ = 3600''$ and $1'' = 4.846\,\mu$rad.

There are various definitions of the year, such as tropical year or sidereal year. Normally the difference will not be relevant, but in the context of velocities I use the Julian year, which is 365.25 SI days. This is the case for the velocity unit au yr^{-1}, for example, which is 4.740 km s^{-1}.

I often use the term 'speed' to refer to the magnitude of the vectorial velocity. Vectors are written using bold font. Thus the velocity is $\mathbf{v}$ and the speed is $v = |\mathbf{v}|$. The scalar (dot) product of two vectors is written $\mathbf{x} \cdot \mathbf{v}$. I frequency use c as the unit of the speed of light.

As is standard in the context of nuclear and particle physics, I often use the electron volt (eV) as a measure of energy, where $1\,\text{eV} = 1.602 \times 10^{-19}$ J. The atomic mass unit is denoted m_u, which I take to be $1.66053904 \times 10^{-27}$ kg. In conventional energy units this is $m_u c^2/e = 931.49$ MeV.

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For dimensionless fractional measures, ppm denotes parts per million. A dimensionless but not unitless quantity is the bit of information, with symbol b, and its multiples kb, Mb, etc., as well as the byte, symbol B, which equals 8 b.

There is a myriad of terms that describe electromagnetic radiation according to whether we are considering power per unit area, per unit wavelength, and/or per unit solid angle, and no rigid convention. *Luminosity* is a power, units W, emitted by a source or received by a receiver. I use the term *intensity* to mean the power per unit area, units $\mathrm{W\,m^{-2}}$. This is common in astronomy, although in other fields this is often called the 'irradiance' or 'flux density'. To describe the intensity per unit wavelength (or frequency), I use the term *spectral intensity*, units $\mathrm{W\,m^{-2}\,m^{-1}}$ (or $\mathrm{W\,m^{-2}\,Hz^{-1}}$). This is sometimes called the 'spectral irradiance' in other sources. The spectral intensity per unit solid angle, the power per unit area per unit wavelength (or frequency) per unit solid angle, is the *spectral radiance*, units $\mathrm{W\,m^{-2}\,str^{-1}\,m^{-1}}$ (or $\mathrm{W\,m^{-2}\,str^{-1}\,Hz^{-1}}$). The integral of this over all wavelengths (or frequencies), the power per unit area per unit solid angle, is the *radiance*, units $\mathrm{W\,m^{-2}\,str^{-1}}$. Finally, in just one place we need the power per unit wavelength, the *spectral flux*, units $\mathrm{W\,m^{-1}}$. I will generally define these less obvious terms again when I use them, but if confused, refer back here.

A brief word on notation. As this book covers a diverse set of topics, it is hard to achieve completely consistent notation across all chapters, so some symbols are used to mean different things in different contexts. For example, P indicates pressure in some places but power in others. Symbols are defined when they are introduced, so hopefully it will always be clear what is meant.

1.6 Chapter overview

The chapters of this book are best read in order because some earlier chapters provide background material for later ones, as shown in figure 1.2. Readers can nonetheless jump straight to chapters that interest them most, as earlier material is cross-referenced where required. I now give a brief overview of each chapter.

Chapter 2 looks at the motivation for interstellar travel, highlighting in particular how it can answer questions in astronomy, planetary science, and the search for life that are not answerable from the Earth (or nearby space) within the foreseeable future, or perhaps ever. I summarize nearby star targets and their known exoplanets.

Chapter 3 describes the basics of rocketry, introducing the all-important rocket equation. The essential concepts of thrust, effective exhaust velocity, and power are explained, and trade-offs between these in terms of travel time and engine requirements are examined.

Chapter 4 covers the fundamentals of Keplerian orbits and orbital manoeuvres. Understanding them is essential for rendezvous at the target planet as well as for solar sailing, for example. I explain the gravity assist and the Oberth effect, which are fundamental topics in astronautics.

The following chapter (5) is on thermal rockets, primarily chemical rockets, illustrating the basic thermodynamics and fluid concepts. We look at various real rockets that use liquid or solid fuels.

Ion engines, covered in chapter 6, are non-thermal rockets that provide a low but long-term continuous thrust. We examine both the principles and their use in the Dawn spacecraft that visited two asteroids.

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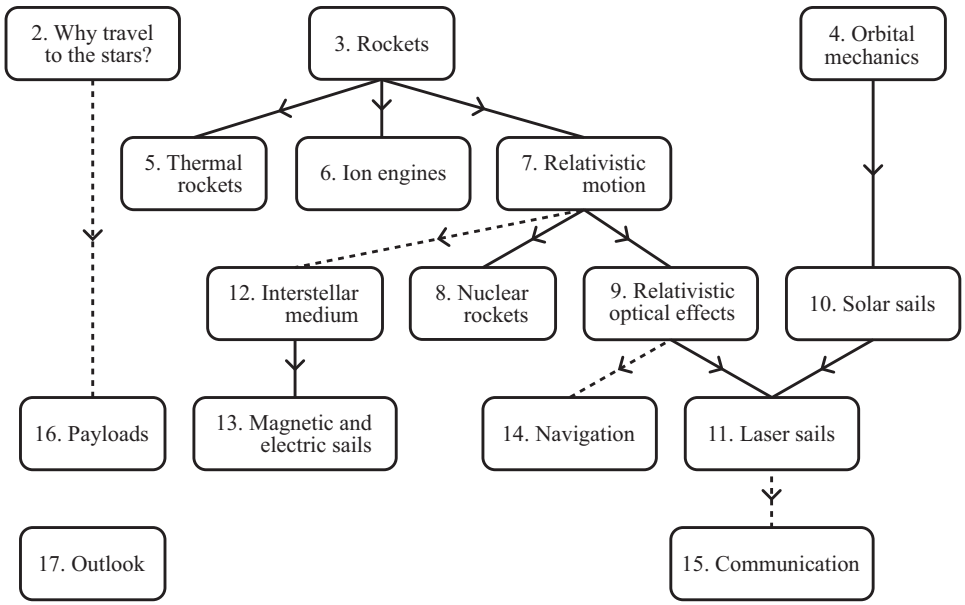


Fig. 1.2 Chapter dependencies. Dashed lines indicate a weaker dependence or one between specific sections.

We look at relativistic mechanics in chapter 7. After briefly revising the Lorentz transformations, we go over special relativity in accelerating systems. This chapter also covers the relativistic rocket equation, the photon rocket, and the mixed matter/photon rocket concept, which we will need in later chapters.

Armed with the appropriate background, we turn to nuclear rockets in chapter 8, covering fission, fusion, and antimatter as sources of energy and propellant. These come in the form of reactors or as miniature explosions coupled to the spacecraft via electromagnetic fields. We examine some prototypes that were built in the 1960s as well as the prototype mission design Daedalus and its successors. Fusion rockets are one of the two most promising ways of getting to the stars quickly.

Chapter 9 continues our exploration of relativity by looking at its effect on optics, in terms of the Doppler effect, aberration, and other consequences of the Lorentz transformations. We will need these in later chapters.

The big drawback of rockets is that they require a lot of their propellant to accelerate the remaining propellant, and so are intrinsically inefficient. Sailcraft overcome this by externalizing the propulsion, either as solar photons or as laser photons. Solar sails are an active area of research and development for interplanetary missions (they have already flown), which we look at in chapter 10 along with the basic principles of photon propulsion. In the following chapter (11) on laser sails, we look at the use of extremely powerful lasers to accelerate sails to relativistic velocities. Time dilation and finite photon travel times render the mechanics of laser-driven sails non-trivial. In addition to the challenging material properties required for the sailcraft themselves, we examine the lasers plus the optical arrays to focus them over large distances. Laser sailing is the other most promising means of travelling to the stars, and we look at some proposed missions.

In chapter 12 we examine the content and properties of the interstellar medium that the spacecraft must travel through. This presents both challenges, such as high energy particle

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impacts, and opportunities for scientific research. We also look at the Bussard ramjet, an ingenious if somewhat impractical idea for collecting and fusing interstellar protons as a source of both rocket propellant and energy.

In chapter 13 we return to sails, this time magnetic and electric sails. These exploit the charged particles in the interstellar medium or the heliosphere of the target star as a way of decelerating an incoming spacecraft.

To boldly go we need to know where we are and where we are heading, so chapter 14 on navigation explores how to determine one's orientation, location, and velocity in space. We start with ranging methods used for interplanetary spacecraft as well as inertial methods. For autonomous navigation in deep space, we examine two approaches. The first uses the three-dimensional positions of the stars; the second uses the timing and direction of pulsars. This latter method bears some relation to global navigation satellite systems, the principle of which I also briefly explain.

The whole point of travelling to a distant star is to return data. The problem of communicating over vast distances is taken up in chapter 15. Diffraction and noise are fundamental issues here. This takes us on a brief journey into information theory to cover concepts such as signal modulation, coding, and channel capacity. Photon fluxes may be so low that we need to consider quantum effects. We will consider the optimal wavelength to use for communication and the relative merits of Earth-based vs space-based receivers.

The penultimate chapter (16) considers what the spacecraft should take in terms of scientific instruments as well as how it can power and control itself. Here we are guided by instruments already used on interplanetary spacecraft. We also discuss the idea of sending relays or swarms of many smaller spacecraft to provide redundancy against failure or so they can operate collectively.

The final chapter (17) first takes a brief speculative look at some of the more outlandish ideas for achieving interstellar travel, such as warp drives and wormholes (those things I said I would not consider). I then conclude with an outlook of the most promising technologies for interstellar travel and how this may develop in the future.

So as not to disrupt the reading too much, I refer to literature sources mostly in the bibliographic essay in the appendix instead of in the chapters. There is a surprisingly large amount of technical literature on interstellar travel, so I don't try to be comprehensive. I instead mention the main sources I have used and those I think will be most useful for deeper study.

Without further ado, let us embark on our voyage by asking why we want to undertake it at all.

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