10 Space in the 21st Century

SOMETIMES as a child, I engaged in the rather pointless activity of wishing I had been born later! This was in the 1950s, when the exploration of the moon and the solar system was yet to begin, and I was impatient to know whether there were little green men on Mars, and what the ringed majesty of Saturn would look like above the horizon of its moon Titan. In this, my imagination was nourished by many evocative pictures by space artists, such as the iconic image in Figure 10.1 by Chesley Bonestell. We now know that Titan has a thick, murky atmosphere, so that such a vista is sadly unlikely to be echoed in reality. I have to admit that there is still something of this childish outlook in me now, and I am still impatient to know how the fundamentals of the universe work, and what it would be like to be able to actually see the sights of the solar system for myself, such as the rings of Saturn or the volcanoes of Jupiter's moon Io.

No one knows what the future holds, but it is possible to imagine a time when physicists will have come up with a *theory of everything* to explain how the universe works, and when the engineers will have solved the problem of interplanetary, interstellar, and maybe even intergalactic travel. My feeling is that there really is no reason to believe we cannot go faster than the speed of light—a speed limit imposed upon us by Einstein's physics. Why should Einstein's theories be the last word in physics, in the same way that Newton's theories seemed unchallengeable at the turn of the 20th century?

Although I can get rather excited about these future prospects, at the end of the day I just have to calm down and accept my allotted position in space and time. From where I am at the moment, it seems unlikely that I will see a fundamental breakthrough in physics that will allow us to understand everything about the universe we inhabit, and how it all works. Coming a little closer to home, if I am lucky I might get to see the first human set foot on the planet Mars. It is interesting to think that, whoever they are, they are almost certainly alive today as I write. And coming a little closer still, I am fairly optimistic that I will see people on the Moon again within the next

G. Swinerd, *How Spacecraft Fly: Spaceflight Without Formulae*,
DOI: 10.1007/978-0-387-76572-3_10, © Praxis Publishing, Ltd. 2008

Figure 10.1: Saturn as seen from Titan, depicted by Chesley Bonestell. (Image courtesy of Bonestell Space Art.)

decade or two. I suppose my impatience stems from the fact that progress does seem so painfully slow; after all, in cosmic terms the Moon is just on our doorstep!

This is not, however, to undermine the achievement of the Apollo program. Some people would say that the late 1960s and early 1970s, when the Apollo astronauts stood on the Moon, was the golden age of astronautics. A team of bold young men—and maybe not so young as far as the astronauts themselves were concerned—made John Kennedy's vision of 1961 happen. Figure 10.2 shows the lunar lander of Apollo 12 on the plain at Oceanus Procellarum. At the time of the Apollo program, I was a teenager and completely enthralled by the whole business! In fact, Apollo is probably one of the reasons why I have spent my career working, teaching, and researching in the area of space. Apollo was inspirational! At the time, with my young idealistic view of the world, I believed that the Americans went to the Moon with the best of intentions—to further our knowledge of this little corner of the universe. But with the benefit of hindsight, and imbued perhaps with a dollop of cynicism that comes with age, I now can appreciate that the main reason for doing it was for capitalism to demonstrate its superiority over Communism. Twelve years before the first moon landing, the launch of the first satellite by the Soviet Union, Sputnik 1, had severely dented American pride, and Apollo was a way of redressing the balance. Despite this, however, Apollo was an outstanding achievement from a space engineering point of view—to say nothing of the courage of the men who actually stood on the surface of the moon. And nothing like it has been seen since. If you had told me in 1972, when Eugene Cernan and Harrison Schmitt took off from the Moon as the final act of the Apollo program, that no one would have returned in 35 years, I would not have believed you! This really does emphasize the one-shot nature of the way it was done as primarily a political act.

If Apollo was the golden age, then unfortunately most of the young people today have missed it. Although many good things have happened in spaceflight since, as we have discussed in this book, nevertheless you could argue that there is currently nothing to inspire young people to get involved in space engineering. Clearly the emphasis in the interim has shifted from space exploration to space applications. This move to use space for communications, navigation, and Earth observation has revolutionized the business and leisure worlds, but it is perhaps not quite so inspirational as, say, opening the solar system to manned space exploration. There is a great need to do something that will inspire young people to get involved. It really is only the young that can dream the big dreams, and make them happen!

In this chapter (which is again longer than average) and the next, I will attempt to discuss some of the developments we may see in the future.

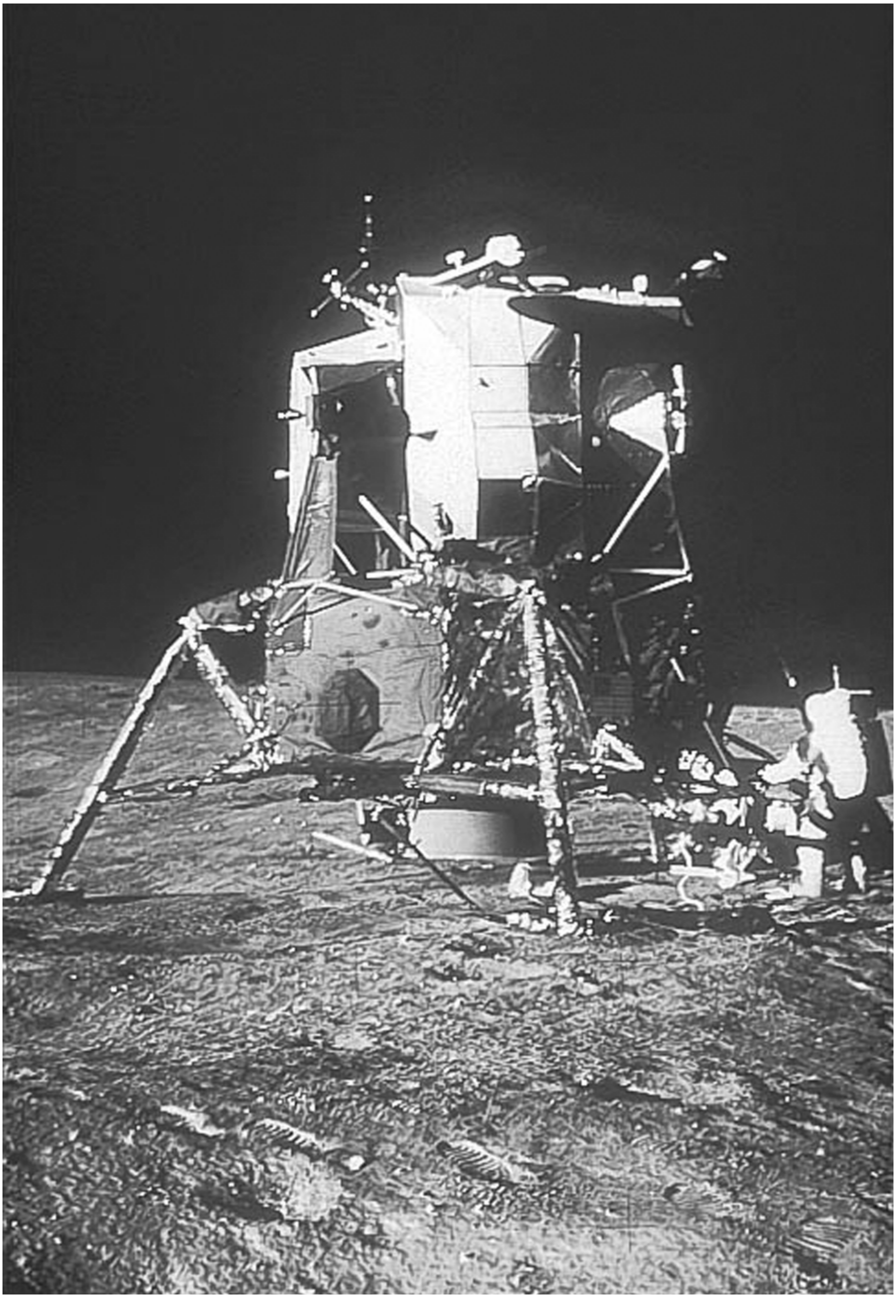

Figure 10.2: The lunar module of Apollo 12 landed in Oceanus Procellarum (the Ocean of Storms) in November 1969. This was the second moon landing of six. When will we see the like of this again? (Image courtesy of the National Aeronautics and Space Administration [NASA].)

Manned Spacecraft

Before we begin this rather speculative journey, we need to briefly discuss manned spacecraft. At this point, I should perhaps repeat the caveat from Chapter 2 about the use of the phrase *manned spaceflight* to mean flights involving both men and women. I know that the phrase may not be quite politically correct, but I dislike the other possibilities, such as "crewed" missions or "peopled" missions.

In earlier chapters we discussed how unmanned satellites are designed, and now we discuss the additional design requirements for manned spacecraft. Space is a hostile environment (Chapter 6), and people are fragile organisms, requiring air to breathe at the right pressure, food to eat and water to drink, as well as an acceptable ambient temperature and a way to get rid of personal waste. These rather obvious requirements translate into the need for a significant mass of hardware and provisions onboard manned vehicles. This trend is readily apparent when we consider current examples of manned space vehicles such as the International Space Station (ISS) (Fig. 10.3), which is

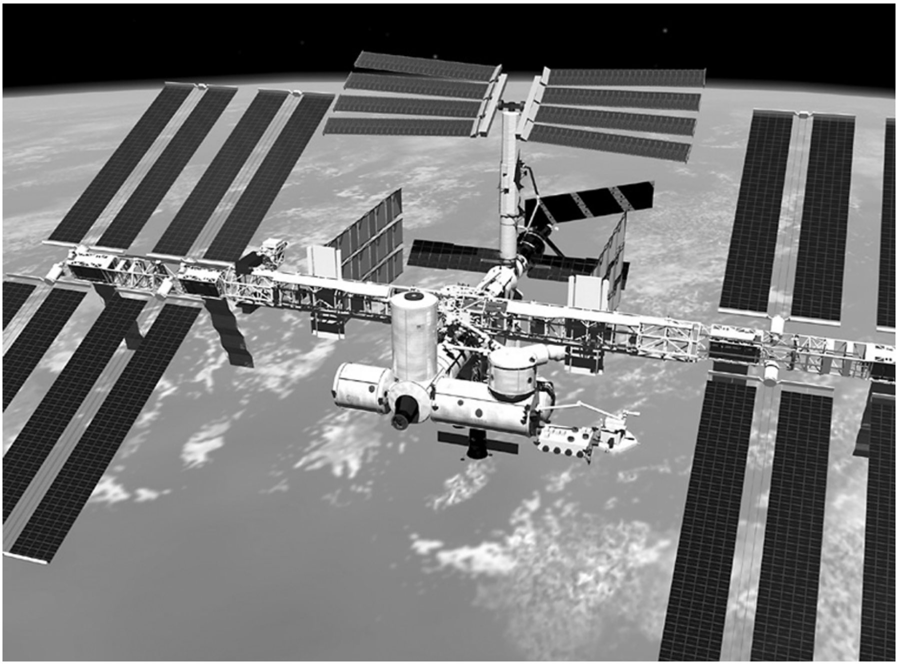

Figure 10.3: The International Space Station (ISS) as it is projected to look when completed in 2010. (Image courtesy of NASA.)

projected to have a mass on the order of 450 metric tonnes when its construction is complete around 2010. Another feature that tends to further increase the mass of manned spacecraft, which is perhaps less obvious, is that of *redundancy*, which entails having backup systems onboard to make the vehicle safe from failures that would threaten the lives of the occupants. Safety-critical items such as elements of the life support system are doubled-up so that if the primary element fails, the backup system can be brought online to ensure the well-being of the crew. This is a major issue in manned vehicle design; a line has to be drawn by the design engineers to ensure a balance between having an excessively massive and extremely safe spacecraft on the one hand, and having a less massive but potentially unsafe vehicle on the other. From the point of view of launch costs, the less massive option is favored. But this is certainly not the case from the point of view of crew safety!

So manned spacecraft are expensive. Not only is the spacecraft hardware to be lifted to orbit more massive, due to the need for life support systems, but the launcher has to be *man-rated*. As we saw in Chapter 5, this means that the launch failure rate has to be reduced from the typical 10% for unmanned launchers to something significantly less than 1% for the man-rated launch vehicle. This is done by increasing the amount of redundancy in the launcher itself, which translates into more mass. Good examples of man-rated launchers, which carry manned hardware to orbit, are the Saturn 5, which sent the Apollo hardware and astronauts on their way to the Moon, and the Space Shuttle. As a consequence, these launch vehicles are some of the most complex, massive, and expensive launch systems yet to be employed. As we look to the future, and the projected expansion of manned space exploration and possibly space tourism, this issue of the cost of access to orbit is one of the main stumbling blocks that will ultimately need to be removed. Some insights into the challenges this poses for rocket scientists were discussed in Chapter 5.

The impact of including people in the design of spacecraft entails not only emulating a suitable terrestrial environment onboard to support life, but also dealing with the aspects of the space environment that are hostile to human life, such as radiation, space debris, and microgravity. The following factors influence how manned spacecraft are designed and operated (also see Chapter 6):

Radiation

In terms of radiation, the main threat to the health of people in space comes from particle radiation (as opposed to electromagnetic radiation). As we saw in Chapter 6, this is essentially made up of energetic (rapidly moving) subatomic particles, such as electrons, protons, and sometimes ions (the nuclei of atoms stripped of their attendant electrons). This type of radiation comes from a number of sources. For people in Earth-orbiting spacecraft, the main offending source is the Van Allen radiation belt, which contains high-energy electrons and protons that have been captured from the Sun and trapped by Earth's magnetic field. However, in low Earth orbits of altitudes less than about 1000 km (620 miles), spacecraft are well below the most intense parts of the Van Allen belt, and are also protected from the majority of direct solar particle radiation by the Earth's magnetic field. As a consequence, astronauts living long-term in the ISS, at an altitude of around 350 km (220 miles), suffer a relatively low level of potentially damaging radiation. However, the use of higher orbits for long-term habitation, for example in the most intense part of the proton radiation belts, which is at a height of about 4500 km (2800 miles), would result in a fatal radiation dose for the crew.

Once the spacecraft leaves Earth orbit and the shelter of Earth's magnetic field, we have another situation entirely. Future trips to other planets will involve astronauts traversing large distances, taking hundreds of days to reach their destination. In these cases, the crew is at the mercy of direct particle radiation from the Sun. At times of solar maximum, solar storms can occur that fling huge quantities of particle radiation across the solar system. If the spacecraft happens to be in the path of one of these outbursts, the level of radiation can be potentially lethal for an unprotected crew. Thus the problem of providing adequate radiation protection would appear to be a potential roadblock for future manned flights to the planets. However, there is a cost-effective two-part solution. First, there must be an effective early warning system that monitors the Sun's output to detect the solar storms, probably using a system of spacecraft sensors in orbit around the Sun. A storm warning can then be communicated to the distant manned spacecraft. Second, there must be a *storm shelter*, which is a small pressurized compartment onboard the manned vehicle where the crew can stay during the solar storm. To protect the crew, you might expect that this shelter needs to be lined with a considerable thickness of lead. However, a better solution, in terms of reducing mass, is to reorient the spacecraft to put a significant mass of existing spacecraft hardware or propellant between the shelter and the Sun. For example, it is estimated that about a half-meter thickness of liquid hydrogen propellant would provide adequate radiation protection for the crew.

Space Debris

This is a risk mainly for manned spacecraft in low Earth orbit (LEO), where the amount of space junk is sufficient to cause concern that a damaging collision may occur. Manned spacecraft that operate long-term in the LEO environment, such as space stations, can be equipped with debris bumper shields (see discussion of Whipple shields in Chapter 6) to protect them from debris impact. For example, a considerable amount of design effort and mass has been invested in the ISS to provide debris shielding. Most of this shielding is deployed on the forward-facing surfaces of the station, as most damaging impacts are likely to be caused by debris coming from the forward flight direction. On the other hand, the Space Shuttle is an example of a manned vehicle that cannot be equipped with such shielding, due to the fact that it has to fly both in the environment of space and in the Earth's atmosphere. The use of Whipple-type shielding would compromise its ability to fly through atmospheric reentry and landing. Over recent years, there has been a growing appreciation of the threat from debris impact to the Shuttle orbiter and its crew. In an attempt to at least minimize the threat to the crew, the vehicle adopts a particular attitude in orbit—upside-down and with the main engines facing forward. In this way the crew is protected from impact with the potentially most damaging debris coming from the forward direction.

Microgravity

Microgravity, or weightlessness, in orbit has been an issue not for the design of manned spacecraft but rather for the effect it has on the physiology of the human occupants. Trying to determine and understand the effects of long-term weightlessness on people has been a major preoccupation of manned space programs since the first orbital flight of Yuri Gagarin in 1961. Considerable medical data have been gathered over the years, with astronauts aboard space stations such as Skylab, Salyut, Mir, and now the ISS staying in orbit for hundreds of days and acting as willing guinea pigs. This means that the effects of microgravity over a period of time typical of, say, a manned flight to Mars can be studied and evaluated. The main physiological effects of weightlessness on people can be summarized as follows:

- Motion sickness: The balance sensors we have in the inner ear rely on the movement of fluid in a normal 1*g* environment to give us information about how we are oriented (lying down or upside-down, for example) and how we are moving around. With the fluid in a weightless condition, the brain has difficulty interpreting what the balance sensors are saying, and there is also a conflict between this information and what the eyes see, which can result in nausea and illness, with some astronauts being affected more than others. The brain usually takes about 2 or 3 days to sort out the new sensory inputs and to adapt to the new environment.

- Redistribution of bodily fluids: On Earth the blood pressure of a standing person decreases with the height above the feet; the pressure in the brain is about one third of that in the feet. Exposure to weightlessness causes a major redistribution of blood, resulting in a bloated face and thin legs—the classic so-called “puffy face and chicken legs” syndrome! The astronaut soon adapts to this situation in orbit, and the body appears to recover its normal function after a short period of time once back in a 1*g* environment on the ground.
- Muscle atrophy: Long periods of weightlessness usually mean physical inactivity, which causes muscles to waste away. This includes the heart muscle, which generally loses mass, with an accompanying reduction in heart rate. To combat this worrying trend, astronauts must spend a significant amount of time in necessary physical exercise, using complex exercise equipment designed for the microgravity environment.
- Bone decalcification: Another significant effect of weightlessness is the cumulative loss of calcium from bones, resulting in bone fragility in the long-term. This trend appears to be reversible once the astronaut is back in a 1*g* environment.

Although people seem to be able to recover from most of the effects of microgravity with time, the issues of loss of bone and muscle mass are a concern in future manned exploration of the solar system. Long-duration spaceflight in weightless conditions means the astronauts are clearly not in the best of physical condition when they arrive at their destination. Intensive physical exercise for the astronauts, and possibly the use of artificial gravity (see below) during the flight may be partial solutions to this problem.

Manned Space Exploration: The Immediate Future

This section discusses manned missions that are (almost) certain to happen in the next 30 years or so. The main elements of this vision are the following:

- The completion and operation of the ISS
- The resumption of manned exploration of the moon
- A manned mission to Mars

Despite a measure of age-induced cynicism regarding these objectives, I nevertheless have a reasonable level of confidence that they will happen. There does seem to be a degree of momentum behind these objectives, particularly with the January 2004 declaration by the incumbent U.S.

president of a new "Vision for Space Exploration". There are other signs as well, such as the retirement of the Space Shuttle fleet in around 2010. The Space Shuttle has been the workhorse of the U.S. space program since its first flight in 1981, and its retirement may at first seem to be a negative development. However, this will actually force changes in the U.S. space program, and encourage a wide-ranging rethink of future objectives and how they can be achieved. This new vision appears to be having a reinvigorating effect on the space program as a whole.

The other main issue is the huge cost of the projects listed above. As such, we can reasonably question the viability of pursuing these goals. In the days of the Apollo moon landings, the huge financial burden was justified by a political motive. But today, in the absence of the Cold War and the political competition that it created, it is reasonable to ask—What can justify and motivate nations and taxpayers to spend huge amounts of money returning to the Moon or going to Mars? It is easy to get immersed in the exciting technical aspects of this vision for the future, but there is no easy answer to this question, to which we will return later.

The International Space Station

At the time of this writing, manned space activity is almost entirely focused on the construction of the ISS in low Earth orbit (LEO). As the name implies, this is an international project involving the space agencies of the United States (NASA), Europe (ESA), Japan (JAXA), Canada (CSA), and Russia (RKA). Its orbit is a near-circular LEO with an inclination of 52 degrees, and a height of about 350 km (220 miles), although the altitude varies a little due to the effects of air drag. When completed in 2010, the mass of the station will be an impressive 450 metric tonnes, and Figure 10.3 shows its final configuration.

The construction began in 1998, and more than 40 assembly flights will have been required to complete the station's construction, the majority of these being Space Shuttle flights. Once completed, the largest overall dimension will be about 110 m (360 feet), the total available electrical power will be on the order of 100 kW, and the pressurized volume accessible to the six crew members will be around 1000 cubic meters (35,000 cubic feet). Beyond completion, the projected lifetime of the station is 6 years, so that it will be scheduled for a controlled de-orbit and atmospheric reentry around the year 2016.

Another impressive statistic is the anticipated cost of the project, about $130 billion, and it is this statistic that has drawn the most attention from the station's critics. The substance of most of this criticism is founded on the belief that the huge budget for the ISS could be better spent on unmanned spacecraft, such as observatories and interplanetary probes. The argument goes that the return in terms of science of unmanned exploration would be much greater, and it is easy to have sympathy for this point of view. The main science research goals of the ISS include astronomy and Earth observation, but we can see (from Chapter 2) that the ISS orbit is not ideal for either of these activities. Other research areas focus on experiments that require one or more of the unusual conditions, mostly related to microgravity, present on the station. These include the continued study of the effects of weightlessness on people, and studies in physics and chemistry, such as materials science. The argument between the two camps has been quite acrimonious at times. One outspoken opponent of manned space exploration is Bob Park, a professor of physics and formally the chair of the Department of Physics at the University of Maryland. His view is rather extreme, but nevertheless sums up the strength of feeling in opposition to the ISS among some American scientists. Park states, "NASA must complete the ISS so it can be dropped into the ocean on schedule in finished form"! (Park points out on his personal Web site that the views he expresses are his own and not those of the University of Maryland.)

My own feelings about the ISS are mixed. I have to admit that I have always thought it to be a very expensive project that is looking for a purpose to justify the cost. It can be argued that nations involved in programs like the ISS gain economic benefit through the development of a high-tech industrial sector, with the associated highly skilled work force. It is certainly the case that there are spin-offs from space technology development, and I am referring to more than just the much-quoted old chestnut—the Teflon frying pan! There is certainly economic benefit to be gained from space industry research and development spinning-off into commercial industry. But generally I would guess that the level of benefit in economic terms is very likely to be less than the investment. So I have to take an alternative tack in justifying expensive manned space programs like the ISS. The fact that the mission ends around 2016 also implies that the ISS will not be a part of the orbital infrastructure in aid of a return-to-the-Moon program or a manned mission to Mars. On the other hand, unlike Bob Park, I am fundamentally a supporter of manned space exploration, and the ISS provides a learning opportunity before more adventurous manned space activity is undertaken. Again my impatience comes to the fore, as progress seems so painfully slow. On reflection, if I were asked to draw up a list of reasons to justify the ISS program, they might be something along the lines of:

- Providing a permanent manned presence in space, and learning how to be there.
- Learning how to build large structures in orbit.

- Learning how to manage large, expensive, complex, and multinational space projects, so that they can be run in an efficient and cost-effective manner.
- Providing inspiration to young people to encourage them to become involved in space engineering and science.

Most of these learning activities will be required in order to take the next steps in leaving Earth and exploring the solar system. I believe that the lessons learned in the ISS program are vital in equipping us for those next steps. However, I am also sure that opponents of manned space activity will still insist that these lessons do not justify the price tag.

Returning to the Moon

The United States has recently declared an intention to return U.S. astronauts to the Moon by the year 2020. This has been spurred by a number of factors, perhaps the main one being a perceived need to regain public enthusiasm for space exploration. Implicit in this statement is a view that a permanent manned presence in low Earth orbit aboard the ISS is not considered sufficiently exciting! I'm sure that motivation has also been provided by the declarations of other nations that have similar intentions. For example, the Chinese space agency have set 2017 as the date for a manned lunar landing, despite the relatively newness of the Chinese manned space program. Another influential feature is the retirement of the Space Shuttle fleet in 2010, forcing major change and new development in the U.S. space program. Although it is important to realize that the U.S. is not the only player in this field, nevertheless I will focus on American plans for a return to the Moon simply because they are sufficiently advanced to give a flavor of how it might be achieved.

The most striking thing about the new NASA plan is that it combines the huge experience gained in the Apollo and Space Shuttle eras of the American space program. The manned vehicle that will replace the shuttle looks very Apollo-like. Initially called the Crew Exploration Vehicle, but now renamed Orion, this spacecraft looks like the Apollo command and service modules (Fig. 10.4). However, it is about three times larger, accommodating four astronauts for the trip to the moon. To launch Orion, a new man-rated launch vehicle is being developed, called Ares 1, using existing components derived from the Space Shuttle and Apollo launch systems. The theory is that this will allow NASA to use tried-and-tested rocket components, and also to benefit from an experienced work force familiar with the manufacture and integration of these components. It is hoped that this will allow a smoother transition to the new operation once the shuttle fleet is retired.

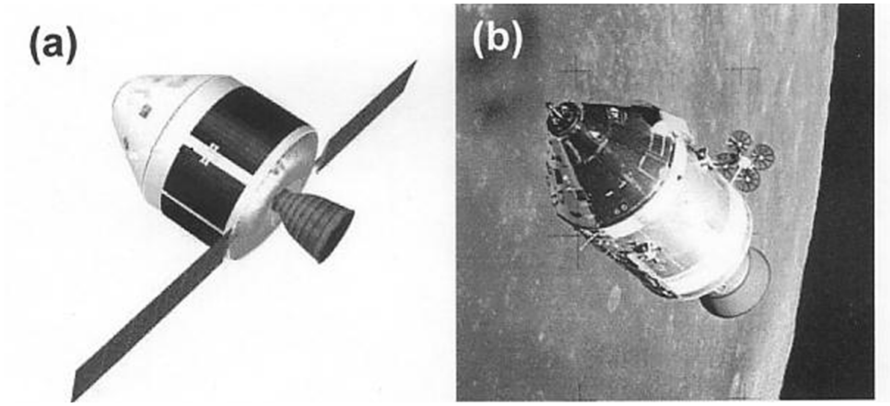

Figure 10.4: The similarity in configuration is apparent when comparing (a) the Orion spacecraft and (b) the Apollo command and service modules, although Orion is about three times larger. (Images courtesy of NASA.)

To land on the Moon, however, requires other equipment, not least of which is a lunar lander spacecraft. NASA proposes developing a separate heavy lift launcher, again composed of Space Shuttle and Apollo components, capable of lifting a payload of the order of 125 metric tonnes into low Earth orbit. This launch vehicle, called Ares 5, will be used to lift the lander spacecraft and a propulsion stage into orbit. It's worth pointing out that although the Ares 1 and 5 launchers are discussed here in the context of the return-to-the-moon program, NASA envisages a wider role for these launch systems involving manned space missions to destinations other than the moon.

So, let's have a look at how all of this new infrastructure to take people back to the Moon fits together, and the way it does is strikingly similar to the Apollo moon landings. The heavy lift Ares 5 launcher blasts off first, taking the unmanned cargo—the lander spacecraft and the propulsion stage—into Earth orbit. Then sometime in the following 30 days the crew takes off in the Orion spacecraft as the payload of the Ares 1 launch vehicle. This new man-rated launch system is much simpler than the Space Shuttle, and as such it is hoped to be more reliable. Once in Earth orbit, the Orion spacecraft will rendezvous and dock with the lander and propulsion stage. After checkout, the propulsion stage rocket engines are fired to boost the whole assembly into a lunar trajectory. Once this maneuver is completed, the propulsion stage is discarded, leaving the Orion spacecraft and the lander docked together for a 3-day cruise to the Moon.

On arrival at the Moon, the main engine of the Orion spacecraft is ignited to take the assembly into a low Moon orbit (Fig. 10.5). The four astronauts

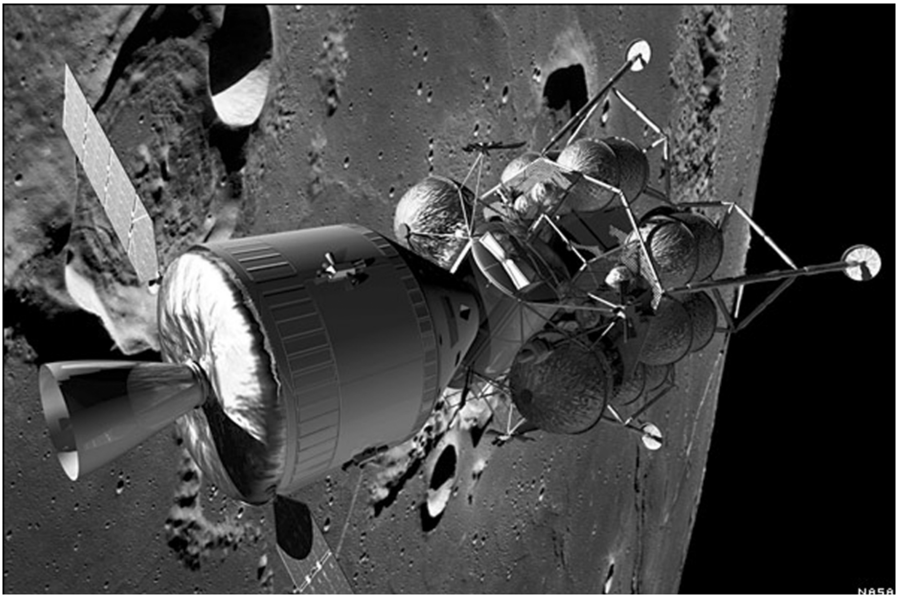

Figure 10.5: The Orion spacecraft docked with the lunar lander in moon orbit. (Image courtesy of NASA.)

then transfer to the lander spacecraft, and undock from Orion, allowing the lander descent engines to fire to take the crew down to the surface. Initially, it is planned that the astronauts will spend 7 days on the surface, while the Orion spacecraft is monitored and controlled robotically in its orbit above. On conclusion of the surface exploration, the crew returns to orbit in the lander ascent module, and then rendezvous and dock with the waiting Orion spacecraft. After transfer of the crew, and the jettisoning of the lander, the main engine of the Orion vehicle is fired to take the astronauts on a trajectory back to Earth. Finally, an atmospheric entry and a parachute descent bring the crew safely home on American soil, probably in California.

Although I personally find the prospect of this shift back to space exploration (as opposed to space applications) exciting, the question of why we should return to the Moon should be addressed. Scientists will always be able to come up with ideas about the scientific exploitation of the unique properties of a lunar base, but do they justify the cost? The price tag for this U.S. initiative is estimated to be about the same as that for the ISS, around $100 billion at least. The opponents of manned spaceflight are hard at work once again bringing criticism to bear on the return-to-the-Moon initiative and claiming how much better value there would be in unmanned, robotic exploration of the Moon.

Another criticism leveled at the new plan is that it has the appearance of a one-shot moon landing program, similar to Apollo, with no prospect of a lasting legacy, such as the establishment of a longer-term manned presence on the Moon. In answer to this, NASA claims the possibility of building some form of semipermanent lunar base using the new launcher and spacecraft infrastructure. Presumably the cargo lofted by the heavy lift launch vehicle can be modified to take components of such a base to the lunar surface. I think this is perhaps the key to justifying the expenditure: the development of a manned lunar outpost in the long-term for exploration of the Moon and to support manned missions to Mars. In addition to the scientific return that this project would give, the Moon can also serve as a proving ground for a broad range of space operations and processes, including the idea of learning to live off the land—in other words, learning the techniques of self-sufficiency that will be useful in establishing future manned bases in other places in the solar system.

Manned Mission to Mars

The first of these "other places" that the space agencies of the world have their eyes fixedly focused on at the moment is the planet Mars. Compared to other possible landing sites in the solar system, Mars is a relatively hospitable planet, with an atmosphere and a reasonable temperature. However, the emphasis here is on the word *relatively*, as future Martian surface explorers will still require the protection of space suits. The atmosphere is composed of mainly CO_2 (carbon dioxide), and the surface air pressure is less than 1% of that on Earth. Despite the tenuous nature of the atmosphere, winds often whip up dust storms that cover large areas of the Martian surface for several weeks at a time. The approximate average surface temperature is a frigid –50°C, and there is also concern that the Martian dust itself may be toxic to humans. And to top it all, due to the fact that Mars's magnetic field is very weak, the surface is pervaded by a flux of solar particle radiation that is attenuated only by the thin atmosphere.

Put in this way, it does make you wonder why people want to invest huge amounts of time, effort, and money to reach Mars! But it is unquestionably the next obvious step in the enterprise of manned exploration of the solar system, with destinations such as Venus and Jupiter ruling themselves out on the basis that they are even more inhospitable. The other main spur for a manned mission to Mars, from the science point of view, is the quest to find evidence of life there. We are not talking about little green men, but more likely the discovery of microbial life. The scientific community is wildly excited about this prospect, since it would tell us something about the occurrence and nature of life in places other than Earth. Again, the anti–manned spaceflight lobby is active in pointing out that this can be done equally well by robotic explorers on the Martian surface, so I guess at the end of the day it is going to be difficult to justify a manned Mars landing on this basis.

This brings us full circle once again to the issue of cost. The cost of a manned landing on Mars is difficult to estimate at this time, but incredible numbers like $1 trillion have been suggested—an order of magnitude increase in spending compared to the ISS or the return-to-the-Moon programs! Clearly, it is difficult to justify this magnitude of expenditure, other than to say things like "it is our destiny." And I think whether we finally go to Mars will hinge on the willingness of the international space-faring community to make this kind of financial commitment.

So how can it be done? Despite the fact that a manned Mars landing may be 30 years away, surprisingly a significant amount of work has been done by space agencies to answer this question. For example, both NASA and ESA (and other space agencies) have developed so-called *reference missions*, to define a Mars landing strategy, and to identify the technologies that will be required to enable the strategy to succeed. Although the reference missions differ in detail, there is nevertheless something of a consensus about the overall approach needed to land people on Mars. Surprisingly, the technology needed for this trip is available now, although some new technologies have been identified that could possibly allow the objective to be achieved at lower cost. The strategy discussed below is a mix of ideas from the various reference missions, but it gives a good idea of how people are thinking about tackling the job.

The basic strategy hinges on the idea of separating the transportation of crew from that of cargo. One day, perhaps 30 years hence, the momentous journey will begin with the unmanned launch of cargo into Earth orbit. At least two such launches will be needed—one to carry an Earth Return Spacecraft, and the other to carry the Surface Cargo Module. Each of these payloads will be of significant mass, on the order of around 150 metric tonnes. After checkout, each spacecraft will be boosted independently out of Earth orbit into a trajectory to take them on their way to Mars. Both of these unmanned elements will use a slow trajectory to Mars, effectively the Hohmann transfer that we talked about in the propulsion section of Chapter 9. The Hohmann transfer to Mars is shown as the slow trajectory in Figure 10.6. The main attribute of this type of transfer, you may recall, is that the amount of rocket fuel required is minimized, reducing overall costs. Nevertheless, to boost each cargo spacecraft out of Earth orbit requires the rocket engines to provide a ΔV (a change in speed) of about 3.6 km/sec (2.2 miles/sec). If a high-performance, but conventional chemical propulsion system is used, this still means that about 80 metric tonnes of the initial 150 metric tonnes will be rocket fuel.

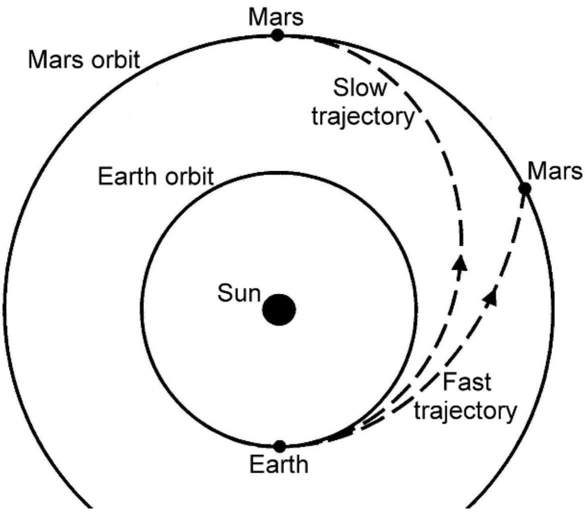

Figure 10.6: Typical transfer orbits to Mars for manned missions. The slow trajectory, the Hohmann transfer, is used for the transit of unmanned cargo. The fast trajectory is used to transfer crew and has a shorter transit time to reduce the effects of microgravity and radiation.

After a trip of 259 days, each of the unmanned spacecraft finally approach Mars on a hyperbolic trajectory (see Chapter 4). To prevent them from just swinging by the planet, their speed needs to be reduced so that they can be captured in an orbit around Mars. The obvious thing to do at this point is to fire rocket engines to nudge each spacecraft into orbit, but this again would cost a significant mass of rocket fuel. To save this fuel mass, some reference missions propose the use of *aerobraking* to achieve Mars orbit. The key to this is the Martian atmosphere. On arrival, each spacecraft dips into the atmosphere and uses the resultant aerodynamic drag to slow down into Mars orbit. Of course, there is a price to pay for this: each spacecraft will require some kind of shield to protect it from frictional heating caused by the rapid passage through the atmosphere. However, calculations show that the mass of this thermal shield is less than the amount of propellant that would be required if the orbit were achieved through firing rockets.

At this point, the paths of the two cargo vehicles diverge. The Earth Return Spacecraft will stay in orbit for a period of years until the astronauts—who at this point are still on Earth—return from their surface exploration. Its job is to take the astronauts home once the mission is completed. On the other hand, the Surface Cargo Module is destined for the Martian surface, where it will wait for the human crew to arrive. As the name implies, this will carry all sorts of equipment that will be useful for the human crew, such as gear for research and exploration, an electrical power plant probably in the form of a nuclear reactor, materials for extending living and laboratory space, surface rovers, and an ascent vehicle to allow the crew to return to Mars orbit at the end of the surface mission. There is also the rather speculative idea of including a fuel production plant to manufacture methane and liquid oxygen from local resources on the surface to fuel the ascent vehicle. The mathematics suggests that an overall saving in mass can be achieved by doing this, but it may not do much for the peace of mind of the crew! So far, so good, but the manned mission has yet to begin!

Once the unmanned spacecraft are in their proper places on and around Mars, and have been checked out to make sure they are in working order, the manned part of the mission can begin. However, to await a suitable planetary alignment, this part of the project will not begin until about 3 years after the launch of the unmanned elements. The Crew Transit and Habitation Module, with a mass of about 150 metric tonnes, will be lofted to low Earth orbit without a crew by a heavy lift launch vehicle. This will be followed within a few days by the crew, probably in an Orion capsule. Once in orbit, the Orion spacecraft will rendezvous with the Crew Transit and Habitation Module to allow the crew to transfer ready for departure. To reduce the travel time to Mars, the Crew Transit and Habitation Module will be boosted into a fast trajectory, as shown in Figure 10.6, at the expense of increased ΔV and fuel mass. This price is considered to be worth paying, in order to shorten the voyage to about 130 to 150 days, so that the harmful effects of microgravity and radiation exposure on the crew can be reduced.

Another way of decreasing the physical effects of weightlessness is to use *artificial gravity* onboard the vehicle. This is the idea of using rotation to produce the sensation of weight. You may have seen films of astronauts being tested for the effects of high launch accelerations by sitting in a big centrifuge. As the speed of rotation of the centrifuge increases, the unfortunate occupants sense a steady increase in their effective weight. In the early days of spaceflight, when astronauts were made of “The Right Stuff” (to quote Tom Wolfe’s title of his book about the early astronauts), these machines were used to subject astronauts to levels of acceleration of 8*g* (and beyond), when the subject effectively weighs eight times their normal weight. Engineers have considered the idea of installing centrifuge-type devices on manned spacecraft destined for the planets so as to combat the physical effects of long-term weightlessness. Another variant is to design the spacecraft so that it consists of two modules attached by a tether system. The two parts are then set in rotation about each other so that the astronauts in each module experience artificial gravity, the level of which is dependent on the rate of rotation. This technology, however, was considered to be inappropriate for the relatively short voyage to Mars, principally on the grounds of increased complexity, mass, and cost.

On arrival at Mars, the Crew Transit and Habitation Module will aerobrake into orbit and descend to the surface, landing within easy walking distance of the waiting Surface Cargo Module so that the surface exploration mission can begin. Figure 10.7 shows an artist's impressions of Martian surface exploration. Hopefully, one day the artist's brush will be replaced by the actuality of photographic images! When the surface stay is over, the crew returns to Mars orbit to dock with the waiting Earth Return Spacecraft. The ascent vehicle is then jettisoned, before the Earth Return Spacecraft is boosted out of Mars orbit for the cruise home. The final act of the mission is a direct entry into Earth's atmosphere, and a parachute descent to a safe landing.

Even in this brief outline, the equipment list for the Mars mission is more extensive than that proposed for Moon missions. This is because the length of stay on the surface of Mars is necessarily much longer, resulting in the need to establish a semipermanent manned outpost during the first landing. This length of stay is dictated by the physics of the motion of the planets around the Sun. To return to Earth, the crew will have to wait for a particular planetary alignment between Mars and Earth, so that the first stay on Mars will probably be many months in duration.

Figure 10.7: Two astronauts explore the Martian surface in an open rover. Artist's impression by Pat Rawlings. (Image courtesy of NASA.)

Manned Exploration of the Solar System

Looking to the future of manned exploration of the solar system beyond Mars becomes a bit of a crystal ball–gazing exercise. For national space agencies, the far future in terms of space program planning means the years 2030 to 2040. Consequently, these plans include a manned mission to Mars, but frankly nothing much beyond that. So to talk about future missions involves guesswork, most of which will miss the mark. However, there are some issues concerning manned spaceflight that are common to the missions we have discussed so far. For such missions to be adequately justified, and ultimately to succeed, there are four key components:

- A good supporting case. These questions need to be addressed: What's it for? Why go? What are the benefits of doing it? Most space exploration is justified on the basis of scientific goals, but other political factors, such as national prestige, work force utilization, and economic benefit through spin-off need to be recognized as valid driving influences.
- An effective team with a common vision of the objectives and how the program can achieve them. With the kind of huge-scale space engineering projects that we have been discussing, such a team will most likely consist of a large number of different nations to share technical responsibilities and program costs.
- The means to go—in other words the technology required to achieve the objective, such as an appropriate launcher capability and manned spaceflight infrastructure.
- An appropriate source of funding. Such missions generally require a huge source of funds sufficient to finance the program, and consequently complete financial planning for the program is required to ensure success. All too often in the past, space projects have suffered from a "stop-go" mentality in terms of funding, governed by political short-termism.

Given the projected cost of a manned landing on Mars, for example, it seems inevitable that deep space missions in the longer-term will continue to be government-sponsored (as opposed to privately funded), and mostly motivated by scientific objectives. Also, we have seen that a good proportion of this cost is driven by the problem of access to Earth orbit—the cost of launch. Currently, this is estimated to be somewhere between about $2000 and $5000 per kilogram launched into low Earth orbit. The other major technical challenge is the development of new space propulsion systems for

Table 10.1: A wish-list of proposed manned space exploration in the 21st century

Year	Mission
2020	Return to the Moon
2030	Manned landing on a near-Earth object*
2035	Permanent lunar base
2040	Manned landing on Mars
2040	Introduction of a single-stage-to-orbit man-rated launch vehicle
2070	Manned landings on the moons of Jupiter (Europa)
2090	Permanent Martian base
2090	Manned landings on the moons of Saturn (Enceladus)

* A near-Earth object is a small body (such as an asteroid or a comet) which has an orbit that comes close to, or crosses the orbit of Earth. Such objects pose an impact threat to Earth (see Chapter 11).

use when the manned spacecraft are beyond Earth orbit. We will discuss these aspects in the next section.

However, let's return briefly to our crystal ball–gazing activity, and ask what kind of missions might be achieved in the 21st century. Table 10.1 lists the anticipated missions over this time period, although it is probably better to call it a wish list, given the shortcomings of the process of so-called prediction in the space business.

Looking at manned missions beyond Mars, exploration of the icy moons of Jupiter would seem to be the next most obvious step. The four major moons of Jupiter—Io, Europa, Ganymede, and Callisto—were discovered when Galileo turned the first telescope in Jupiter's direction about 400 years ago. With Jupiter being five times more distant from the Sun than Earth, the level of solar illumination and heating is around 25 times less (the inverse square law again!) than at the Earth. Generally Jupiter's moons are rather cold, inhospitable places, with the surface temperature of Europa, for example, being around –160°C. However, as unlikely as it might seem, Europa has been identified as a place in the solar system where life may have evolved, and scientists are enthusiastic about the idea of sending robotic and ultimately manned missions there.

The story of potential life on Europa is an intriguing one, which began with the entry into Jupiter orbit of the unmanned Galileo spacecraft in September 1995. Soon afterward, the spacecraft returned images of the icy surface of Europa, such as that shown in Figure 10.8. At first glance, the image looks rather uninteresting. But a more careful examination shows that the icy surface of Europa has fragmented at some time in the past into

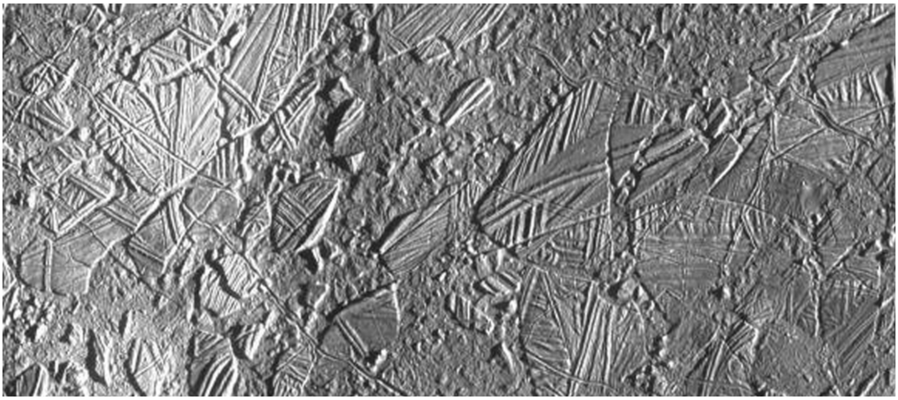

Figure 10.8: An image of the icy surface of Europa, taken by the Galileo spacecraft. (Image courtesy of NASA/Jet Propulsion Laboratory [JPL]—Caltech.)

icebergs floating on a liquid ocean, which appear to have drifted off-shore before the ocean refroze. The implication of this is the belief that beneath the icy crust of the moon there is an ocean of liquid water! It is thought that the water remains liquid because it is heated from below by hot volcanic vents on the seabed. As Europa orbits Jupiter, it is subject to tidal forces that squash and stretch the moon, and it is thought that this drives the volcanic activity. How does this lead us to believe there is life there? Well, similar volcanic vents have been found deep in Earth's ocean trenches. These vents are so deep, in fact, that there is no solar energy to sustain life, but marine biologists have found life there, nurtured and maintained by the heat and energy from the volcanism. Scientists believe that a similar process may be happening in Europa's ocean, and the exciting thing is that the life there may have evolved beyond the purely microbial. Arthur C. Clarke picked up on this fascinating idea some years ago in his *Odyssey* series of novels in which he crafts a fine drama around this speculation about extraterrestrial life.

The Cost of Access to Orbit

As we have seen, every kilogram of people, hardware, and propellant that is lifted into Earth orbit costs several thousands of dollars. It is mainly this huge cost of access to Earth orbit that results in the astronomical sums of money needed to fund manned exploration missions. Finding a solution to this fundamental obstacle would result in opening up the new space frontier. However, it is a hard nut to crack.

The ideal solution would be the development of a "Beam me up, Scotty" machine, similar to that used in the *Star Trek* movies. Scientists are giving serious thought to this, and some of them believe that such a transportation device could be operational by the turn of the 22nd century. Current progress on this is slow, but physicists are seriously engaged in developing experiments to demonstrate the transportation of single atoms—I guess you have to start somewhere.

Man-Rated Launchers

In the absence of transporter beam technology, we are back to rocket systems as a means to reach orbit. One way to approach the problem is to divide it into two strands—one dealing with the launch of people, and the other with lifting large amounts of cargo into orbit. If we look first at the issue of launching crew into orbit, there are new initiatives underway (as we have seen) that are at opposite ends of the spectrum in terms of complexity. On the one hand, with the retirement of the Space Shuttle, there is the development of the new manned Orion spacecraft, accompanied by the man-rated Ares 1 launch vehicle. The philosophy here is one of trying to decrease cost, and increase reliability by going back to a simple launch system with a viable escape system for the crew. Fundamentally, the Space Shuttle is a complex machine, and NASA has found it hard work and very costly maintaining an acceptable reliability of 99%, if indeed this can be considered acceptable for a man-rated launcher. On the other hand, there is the approach of developing the complex single-stage-to-orbit (SSTO) launch system that we discussed in Chapter 5. There is no doubt that the cost of access to orbit for crew (and indeed small unmanned payloads) would be considerably reduced, as the goal of such a program is to develop a system that is totally reusable with the operating characteristics of an airplane. Despite the severe technical challenges this poses, it does not seem unreasonable that such a vehicle will be developed through civil and military research programs within, say, the next 30 years. As such, it could be easily integrated into the manned exploration programs around 2040 and beyond.

Unmanned Cargo Launchers

The problem of low-cost access to orbit of large unmanned payloads is more difficult, however. I suppose it is possible that a large cargo version of the SSTO vehicle may be developed, but given the technical difficulties of developing such a vehicle anyway, it seems unlikely that it will ever be able to carry a large payload mass—say, in excess of 10 metric tonnes—into orbit. To solve this, one option is to take the brute force approach of developing large, unmanned cargo carriers, using tried and tested rocket components. The aim would be to develop a reliable heavy-lift workhorse, able to loft payloads of the order of 150 to 200 metric tonnes into low Earth orbit to satisfy the requirements for future manned exploration programs. It is difficult to predict the likely cost per kilogram of payload into orbit, but it would seem reasonable to have a design target of halving the launch costs.

Space Elevators

Another, perhaps longer-term, solution to the problem of reducing the cost of access to orbit is the space elevator. This is the idea of having a cable stretching from Earth's surface to a point beyond geostationary orbit (Fig. 10.9). The cable is anchored to Earth's surface at the equator, and the length of the cable is such that the forces due to Earth's rotation, which tend to fling the cable outward away from Earth, are exactly countered by the weight of the cable, tending to cause it to fall toward Earth. In this way, there is always tension in the cable, so that it will stay erect above the anchor point. Some kind of elevator vehicle can then climb the cable like a beanstalk to carry payloads to orbit. Once the elevator reaches geostationary height—around 36,800 km (22,200 miles)—the payload becomes weightless, so that launching it into orbit is just a matter of gently nudging it out of the elevator. Such a structure has the potential to deliver crew and cargo to orbit at a fraction of the cost incurred by using rocket-powered launchers.

Although this arrangement sounds unlikely, the theory is sound and such a structure is possible in principle. However, there are all sorts of practical difficulties that put its construction beyond our reach at present. The main one is that we currently do not have a material that is light enough and strong enough to withstand the tension in the cable, which reaches a maximum at geostationary orbit altitude. For example, the requirement

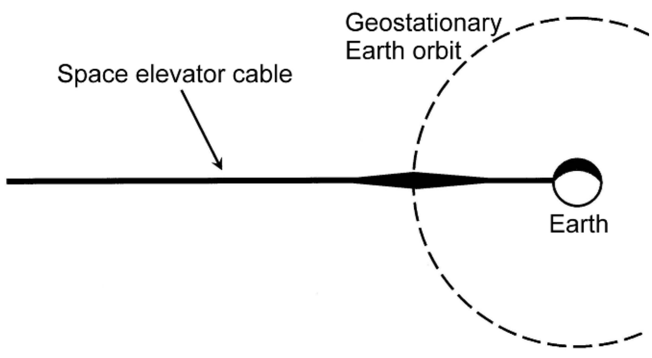

Figure 10.9: A diagram of the space elevator (not to scale). The cable is likely to be tapered, being fattest at geostationary height where the tension is greatest.

exceeds the ability of steel to sustain such a structure by a factor of the order of 100. Materials scientists are working to meet this challenge, but unfortunately it looks like it will be some time before the space elevator solves the problem of low-cost access to Earth orbit.

Space Propulsion

As we have seen, the primary rocket engines used on launchers need to be big to produce enough thrust to lift the weight of the vehicle. Generally speaking, launching things vertically from Earth's surface tends to be a brute force affair, with thrust levels measured in multiples of MegaNewtons, and flight times confined to a few minutes. However, once in orbit around Earth, or in interplanetary cruise, we have a bit more flexibility, in that vehicle weight is not so much a factor so that thrust levels can be smaller and burn times longer.

To date, the vast majority of unmanned exploration of the solar system has been achieved using chemical space propulsion, and doing a simple calculation it can be shown that the best ΔV (change in speed) we can get from an unstaged chemical propulsion system is around 10 km/sec (6.2 miles/sec). This is on the basis of a spacecraft that consists of only the rocket engine, the fuel tanks, and the propellant; it has no payload! Although this is a rather pointless spacecraft, nevertheless it makes the point that currently spacecraft and mission design is significantly constrained by the existing status of propulsion technology. When we look at future missions to the planets, such as landing robotic and human explorers on the surface of Europa, the ΔV requirements are well in excess of 10 km/sec. This is a fundamental obstacle that needs to be overcome by technical developments in space propulsion, and in this section we take a brief look at some of these. Currently, there are two main contenders: nuclear electric propulsion and nuclear thermal rockets.

Nuclear Electric Propulsion (NEP)

Electric propulsion systems have been developed over many years and have already flown on unmanned spacecraft. There is a fundamental difference between chemical and electrical propulsion systems. With a chemical system the energy required to accelerate the propellant out of the rocket nozzle is obtained from burning the fuel/oxidizer combination. The speed we can impart to the vehicle is fundamentally limited by the amount of energy contained in the chemical propellants. However, an electric propulsion system is separately powered, inasmuch as the energy to accelerate the

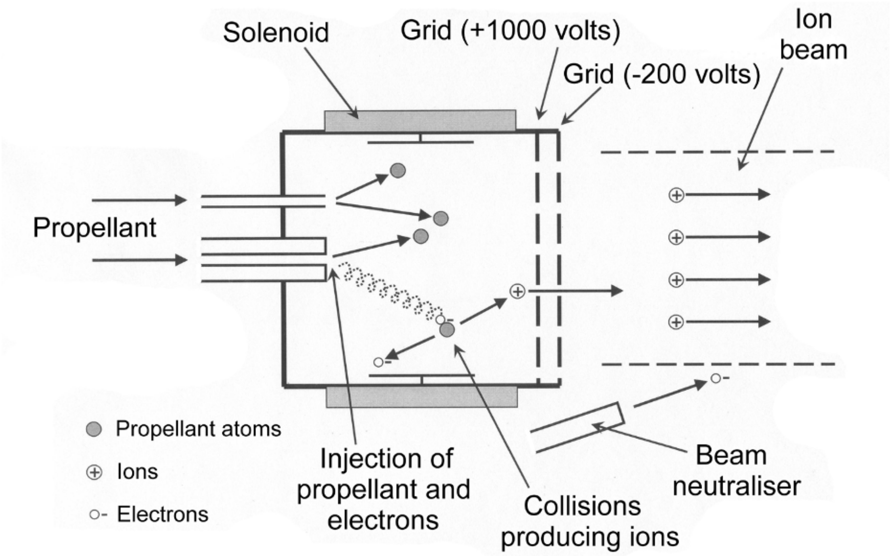

Figure 10.10: A cross-section through the cylindrical ionization chamber of an ion drive.

propellant comes from a separate source, and so in principle is unlimited. As the name implies, this separate source is electricity, and this can be generated using sunlight (solar panels) or nuclear energy.

A common form of electric propulsion, called the *ion engine*, is shown in Figure 10.10, which depicts a simplified cross section through a typical ion engine. The engine is a squat cylindrical chamber, a bit like a paint can, into which the propellant is injected. In the ion engines that are used in small unmanned spacecraft, the diameter of the cylinder is around 10 cm (4 inches) in size, and the usual propellant is an inert gas, such as argon or xenon. As well as the propellant, electrons are also injected into the chamber from a heated hollow tube, called a hollow cathode. Surrounding the cylindrical surface of the chamber are solenoids—basically electromagnets—that produce a magnetic field within the chamber, causing the electrons to corkscrew around the magnetic field lines (see Figure 6.7 in Chapter 6). In this way, the likelihood of collisions between the electrons and the propellant atoms is increased, and these collisions cause ionization of the propellant. In other words, electrons are stripped from the propellant atoms, causing them to acquire a positive electric charge. These positively charged propellant atoms are called ions. (There are a variety of ways of producing the population of ions in the chamber other than the use of a hollow cathode described here.) At the exit of the device, there are metal grids to which a voltage is applied to accelerate the ions out of the device, forming a high-speed ion beam. Finally, to prevent the spacecraft acquiring a huge negative electric charge, electrons are squirted downstream into the ion beam by a beam neutralizer, to allow the electrons to recombine with the propellant ions.

The resulting exhaust velocity of the device is typically on the order of 50 km/sec (30 miles/sec)—about 10 times higher than that of a high-performance chemical system—but the achievable mass flow rate is much smaller. As a consequence, a typical ion engine has a large specific impulse (which is good), but a low thrust level (which is not so good). Recalling the discussion about specific impulse in Chapter 5, this means that, all other things being equal, the ion engine will produce about 10 times more ΔV (speed change) for a given mass of fuel than a chemical system. However, the low thrust means that it will take a long time to do so. Fortunately ion engines can operate for thousands of hours, so the tiny accelerations that they produce can build up large ΔVs, but one has to be patient. It is a 0 to 60 mph in 2 weeks kind of performance! For an ion engine powered by solar panels, with an input of around 1 kW of electrical power, the level of thrust is quite tiny—on the order of 1/20th of a Newton!

To date, this kind of system has been used on unmanned spacecraft for things like orbit control of spacecraft in Earth orbit, or for missions to the Moon and near-Earth asteroids. But the question is, Can the system be scaled up to produce a useful means of propelling large manned spacecraft? The obvious route is to use a nuclear reactor power system to increase the power levels to the hundreds of kW level. Research into the feasibility of such NEP systems has been underway for many years, but such a system is yet to be flown in space. Using some simple calculations, we can scale up the 1 kW system mentioned above to a power input of, say, 500 kW. The configuration of such an ion drive is speculative, but we can envisage this power input supplying maybe five ion engine units each 60 cm in diameter. A quick calculation gives a thrust level of around 15 N, which (if we recall our informal definition of a Newton) is a force equivalent to the weight of about 15 small apples. Although this is more useful than the 1/20th of a Newton we had before, even so it is questionable whether an ion drive can be scaled to provide a propulsion system for manned spacecraft, which tend to be large (of the order of 100 metric tonnes in mass). We will come back to this in our summary later.

Another issue that affects the dynamics of nuclear powered propulsion systems is the mass of the power plant. The nuclear reactor is likely to be of a significant mass, which will add to the already burgeoning mass of a manned spacecraft. This is hard to estimate, but the mass of a 500 kW reactor, for example, might be around 3 metric tonnes.

Nuclear Thermal Rockets (NTRs)

The nuclear thermal rocket is another propulsion technology where the energy is provided by a separate source, once again a nuclear reactor. But the mode of operation is different from that in the NEP system. To operate a NEP device, a reactor is used to produce electricity to power the system. However, in the NTR the heat produced by the nuclear reactor is not converted to electricity. Instead it is used directly to heat the rocket propellant, energizing it to produce thrust. NTRs have been developed and tested over many years, but again the technology has not been flown in space.

The NTR shown in Figure 10.11 is referred to as a *solid-core configuration*, which is the simplest design to construct. In concept, the operation of the rocket is relatively straightforward. Liquid hydrogen propellant is passed through the reactor core, acting to cool the reactor and to heat the hydrogen to temperatures of around 3000°C. This superheated hydrogen is then expanded out of the engine nozzle to produce thrust. This engine can produce a high thrust for relatively long periods of time, up to about an hour, and has a specific impulse of around 1000 seconds. This specific impulse is an improvement over the best chemical propulsion by a factor of two, so that about twice the ΔV is achievable for a given mass of propellant. To give an example of what this means in terms of numbers, let's suppose we use a 200 kN thrust solid-core NTR with a specific impulse of 1000 seconds to propel a spacecraft with an initial mass of 150 metric tons. If we fire the engine for an hour, the burn would result in a ΔV of 6.5 km/sec (4.0 miles/sec), so that we are getting a performance that is really useful for the propulsion of manned exploration missions. The mass breakdown for this example is about 73.5 metric tonnes of fuel, 6.5 metric tonnes of NTR, and 70 metric tonnes of useful payload. Also, by using different designs of NTR, the specific impulse can be further increased up to around 2000 seconds, so in principle the mass of fuel can be reduced further.

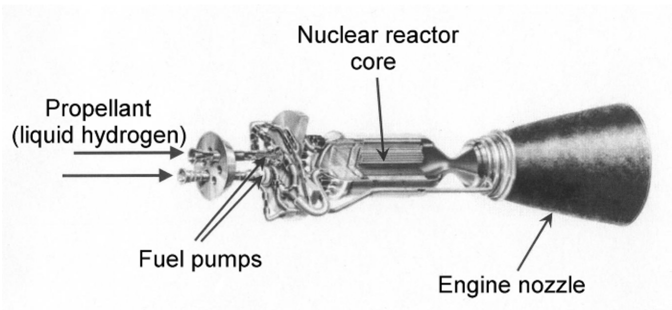

Figure 10.11: A cutaway diagram of a solid-core nuclear thermal rocket. (Backdrop image courtesy of NASA.)

Comparison of Space Propulsion Technologies

To compare the space propulsion technologies we have so far considered, I have taken the example of the Earth departure engine burn to transfer a manned spacecraft onto a trajectory to Mars. Table 10.2 compares the propulsion technologies; we can see that a fixed ΔV of 3.6 km/sec (2.2 miles / sec) and a fixed initial vehicle mass of 150 metric tonnes are assumed in all cases. The chemical engine is equivalent to one Space Shuttle main engine, and the NEP system is assumed to be powered by a 500-kW nuclear reactor. The characteristics of the NTR are those adopted by NASA in its Mars reference mission.

The table shows that in terms of minimizing propellant, the NEP ion drive wins easily. However, the thrust level of the ion drive is so small that the time to execute the rocket burn is ridiculously long, ruling it out as a practical proposition. This issue effectively discounts the use of NEP for manned exploration, where vehicle masses are generally large. The use of NEP is perhaps more appropriate for operating large unmanned interplanetary spacecraft in the 20-metric-tonne class. Such projects have been proposed in the past for missions such as the robotic exploration of Jupiter's system of icy moons, but they have yet to get off the drawing board. The table shows that the NTR is promising in terms of propulsion for manned missions, with not only an appropriate thrust level but also a useful payload mass.

However, there are other issues with operating nuclear powered spacecraft that we have not yet mentioned. The first and most obvious, perhaps, is the issue of the radiation that the reactor produces, and the harmful effects that this has on the crew. We have already seen that the

Table 10.2: A comparison of propulsion technologies, based on Earth departure ΔV for a Mars mission. Note: An initial mass of 150 metric tonnes is taken for all cases, as being representative of a manned spacecraft.

Type of engine	Chemical	NEP	NTR
ΔV (km/s)	3.6	3.6	3.6
Initial mass (metric tonnes)	150	150	150
Specific impulse (sec)	450	5000	960
Exhaust velocity (km/sec)	4.4	49.1	9.4
Thrust (N)	2,000,000	15	200,000
Burnout mass (metric tonnes)	66	139	102
Fuel mass (metric tonnes)	84	11	48
Burn time	3 minutes	393 days	37 minutes

mass of the reactor is significant, but there is also the requirement for additional mass in the form of radiation shielding to protect the astronauts. Finding the best place for the reactor, and the accompanying shielding, relative to the crew's living space will have a major impact on the vehicle design. A significant mass of thermal radiators will also be needed to ensure that the thermal output from the reactor system is adequately dissipated. A final issue, perhaps of a political nature, is that the NEP and NTR systems both carry the label "nuclear." Although it is intended to use these nuclear-powered systems only in space, where any harmful environmental effects are negligible, nevertheless their operation will inevitably attract opposition from the increasingly vocal "Green" lobby. The focus of concern is not so much the space operation, but the requirement to launch the systems into orbit. It is certainly true that a launch failure would scatter radioactive pollution throughout the atmosphere and on the ground.

Although there are other (fairly wacky) ideas to solve the problem of space propulsion, many of these appear to be viable only in the distant future. Unfortunately, none of the more sensible ideas come anywhere near the propulsion systems we see routinely in science-fiction movies like *Star Wars*. The kind of energy source that will allow manned vehicles the size of small airplanes the freedom to launch into space, fly across the galaxy, land on other planets, and then return, simply escapes our ingenuity at the moment. Hollywood space engineering has always been a lot easier than the real thing!

Space Privatization and Space Tourism

Moving away from government-sponsored space programs for a moment, it is interesting to ask what the future holds for space privatization and the expansion of the booming terrestrial tourism industry into the new arena of space.

Space Privatization

In our discussion above, concerning manned space programs, we have painted a picture of huge sums of money being spent over decades of time, where the payoff comes mostly in terms of the advancement of scientific knowledge and possibly political prestige for the participating nations. Put in this way, it is easy to appreciate why it is hard for private industry to get involved, given the normal requirement of a good financial return on investment and within a reasonable time scale. Private industry's need to make a fast buck is a philosophy that does not fit well with the overall enterprise of manned space activity. Perhaps the only way around this roadblock is through the development of space tourism, and this is something we will come back to in a moment.

Despite views to the contrary, there is a good deal of private industry involvement in space activity, and to find out where this is happening, you just need to ask which bits of space turn a profit. The most profitable space application over many years has been that of satellite communications. Over time, intercontinental telephone traffic has increased greatly, and one of the best ways of doing this is through satellites, predominantly in geostationary Earth orbit. And there is a good return on investment to be had by the spacecraft owners. Earth observation is another contender that shows promise in this respect. The idea is a simple one—that of selling satellite images of Earth to users who need the data for a variety of reasons, including searching for Earth resources, weather forecasting, disaster assessment and management, the planning of large civil engineering projects, map making, and even agriculture. A number of private ventures have tried to turn a profit doing this, but this is generally only possible if the costs of the spacecraft and the launching are removed from the equation. Earth observation is not strictly a profitable activity at present, but the potential is there for the future if we can drive down spacecraft and launch costs.

Beyond communications and Earth observation, perhaps the next most promising commercial candidate is satellite navigation (satnav), which we discussed briefly in Chapter 1. We are all familiar with satnav systems these days—for example in cars—that operate using the American military Navstar GPS system. However, in around 2012 a civil system will be launched by the European Union called Galileo, and the intention is to charge users for access to the system. There are some issues here that muddy the waters regarding Galileo's profitability, such as convincing people to pay to use it when there is a perfectly acceptable and free alternate system in the form of GPS. There are some fairly long-standing political and financial issues with Galileo that people are grappling with at the moment, but if these can be resolved, there is great potential for turning a good profit.

Finally, although the list is perhaps not exhaustive, the provision of launch services is the last obvious example of commercial space enterprise. There are a number of commercial launch companies in the U.S., Europe, and Russia that market and sell launch opportunities to governments and private customers. Arianespace, which operates the Ariane family of launch vehicles, became the first such commercial space transportation company in 1980, and continues to be one of the largest providers of rides to orbit.

So, currently there is good evidence of commercial activity in unmanned

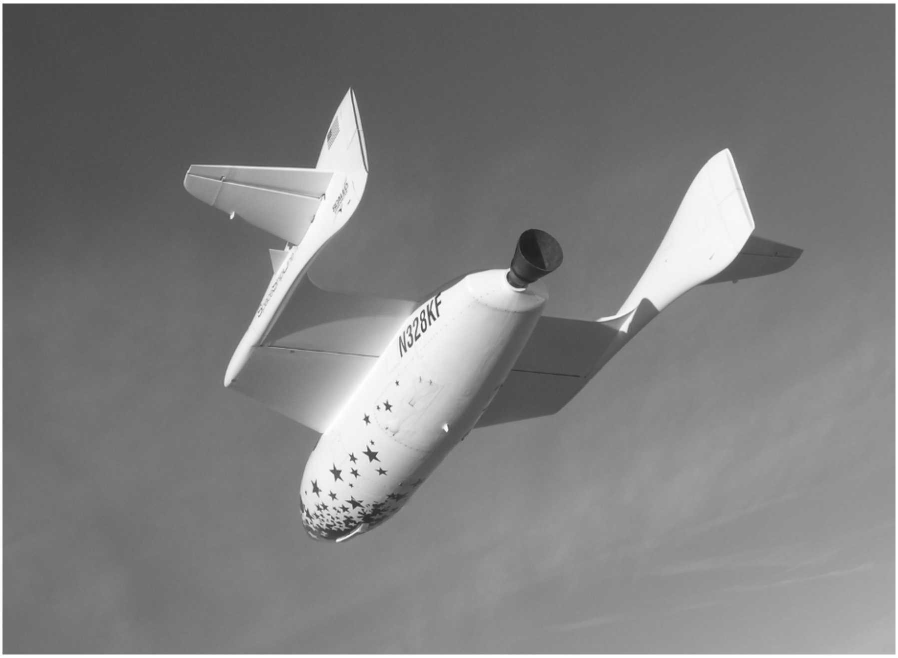

Figure 10.12: The X-prize winning SpaceShipOne on its descent after reaching in excess of a 100-km altitude in 2004. (Copyright © 2004 Mojave Aerospace Ventures LLC. Photograph by Scaled Composites. SpaceShipOne is a Paul G. Allen project.)

space applications, but what of the privatization of human spaceflight, given the issues of cost, time scales, and return on investment? A first step was taken in 2004, when a piloted vehicle called SpaceShipOne (Fig. 10.12) won the so-called X-prize of $10 million, which was set up to stimulate private investment in the development of manned spaceflight technologies. To win the prize, SpaceShipOne had to demonstrate the first human spaceflight to an altitude in excess of 100 km (62 miles) in a privately developed and operated vehicle. Although this is a considerable achievement, one very important point should not be missed here: the vehicle reached orbital height but did not achieve orbital speed. As we discussed in Chapter 2, to enter orbit at a 100-km altitude requires traveling horizontally at about 8 km/sec (5 miles/sec), and in terms of technical achievement it is the attainment of orbital speed that is the difficult part. Acquiring this speed demands the input of huge amounts of rocket-powered energy, which makes conventional launch operations so risky and expensive. So in a way you could say that the X-prize competition missed the point. However, as a consequence of this first privately funded manned spaceflight, a number of commercial companies have jumped on the bandwagon, and are proposing to build a number of such spacecraft to take people to orbital height. The motivation for this investment is tourism, and in the first instance, seats will be sold to passengers at around $200,000 each. For this fee, paying customers will experience the view of Earth from 100-km altitude, and a period of a few minutes of weightlessness at the top of the trajectory when the vehicle is in unpowered free-fall. So here, finally, we begin to see a motivation for private investment in manned spaceflight—that of space tourism.

Space Tourism

The first fare-paying space tourist was Dennis Tito, who visited the International Space Station for 7 days in 2001. Since then, a handful of others have followed him to enjoy the experience of life in orbit. However, a ticket costs about $20 million. For Tito, that was about $5000 per kilogram to lift him into orbit, and then a room rate of about $2.8 million per day! Clearly the opportunity to take a holiday in space is not available to most people because of the cost of access to orbit. The suborbital flights mentioned above, with a ticket price of around $200,000, is a way of bypassing this obstacle, but nevertheless cost is still the fundamental barrier to the exploitation of space by the tourism industry.

Inevitably, the key to opening up space to the tourist market is access to Earth orbit that is cheap, reliable, and safe. Once again we have gone full circle, and arrived back at the need for the development of a single-stage-to-orbit man-rated launch vehicle with the reliability and operational characteristics of a civil airliner to open up this new commercial opportunity. As we mentioned in Chapter 5, this is a major technical challenge, requiring considerable investment probably on the back of a military research and development program. If this is how it happens, then it will not be the first time that commercial enterprise has benefited from the fruits of military research. In terms of time scales, I stuck my neck out earlier in this chapter to suggest that such an SSTO launcher may be operational within 30 years or so, so again patience is the order of the day!

This is not the end of the story, however. Once the problem of orbital access is solved, there is still a need to develop space infrastructure in orbit and beyond, to take passengers to their intended holiday destinations. For example, I have always thought how great it would be to take a weekend break to see the rings of Saturn, or to spend a week on an elevated lunar monorail taking in the splendors of the lunar landscape—a bit like a lunar equivalent of a Canadian Rockies scenic railway ride but without the weather (and of course stopping off for a quick snack at the Tranquillity Base

McDonalds along the way). The principal challenge here is to develop a safe and reliable means of space propulsion that will reduce the travel times to the distant planets from our current expectation of years to a few days—a tall order indeed.

No doubt the development of space tourism will be incremental, starting with Earth orbit hotels, and then progressing to the Moon and beyond as space propulsion technology develops. However, it is clear that real space tourism—people vacationing throughout the solar system for a price that the majority can afford—is going to take a long time, and unfortunately I have no expectation that trips to Saturn's rings will be available within my lifetime!

In the next and final chapter, we take a brief look at a couple of issues that relate to the necessity for us to be fully involved in the business of safe and inexpensive access to space.