16 Payloads

The payload can be considered as everything the spacecraft carries that is not related to propulsion. We examined navigation and communication in previous chapters. Here we look at the scientific instruments that an interstellar spacecraft may carry and what they would be used for, consider possible sources of onboard power, and outline the need for autonomous control of the spacecraft. We also touch briefly on the idea of spreading a mission's payload across multiple spacecraft in the form of swarms or relays.

16.1 Scientific instruments

The main purpose of an interstellar spacecraft is to carry instruments to the target star system, to enable these instruments to obtain data, and to transmit the resulting data back to the Earth. The main targets of scientific interest are the star itself and planets around the star. Further objects of interest include other planetary bodies in the star system, such as comets and moons, any stellar disk, the star's heliosphere, and the space between our Sun and the star, as outlined in chapter 2.

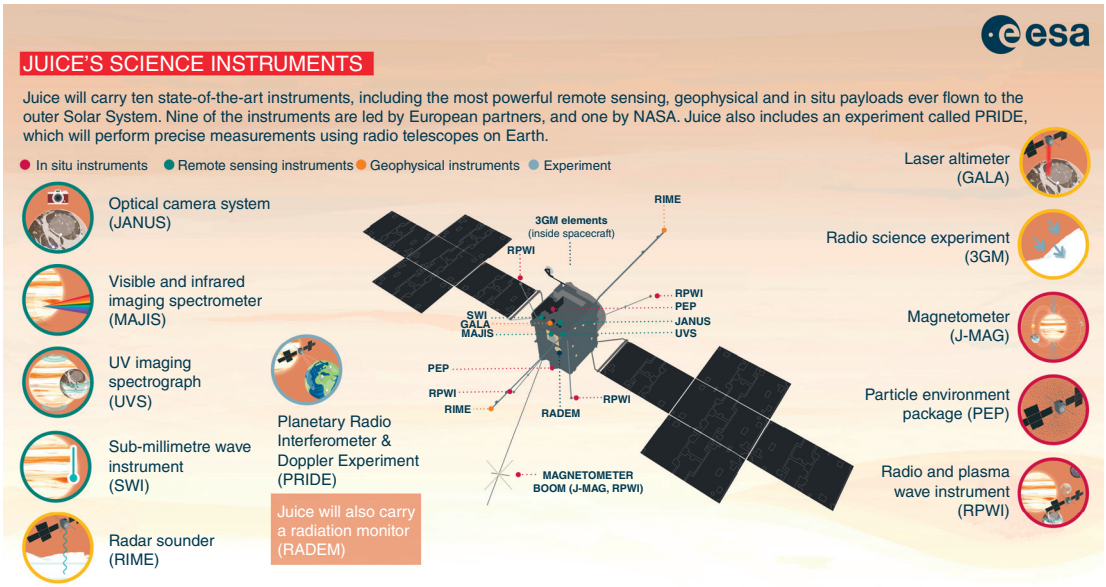
To best study these targets, a range of instruments are required. Just as is done for missions in the solar system, the instruments would be optimized for the specific target, for example whether the planet is known to be a small rocky planet, a gas giant, or an intermediate-mass icy world. Instruments nonetheless need to be sufficiently general to make discoveries and to allow them to adapt in response to new information that will inevitably be discovered about the target system during the spacecraft's long journey from the Earth.

The types of instrument would be broadly similar to those carried by interplanetary spacecraft to explore our solar system. A few example missions are Mars Express, Europa Clipper and JUICE that will explore Jupiter and its moons, and New Horizons that visited Pluto and the Kuiper belt. An overview of the JUICE instruments is given in figure 16.1.

Instruments that fly on interplanetary spacecraft often have masses of tens of kilogrammes and require powers of tens of watts. The New Horizon instruments were relatively light and low power, of the order of a few kilogrammes and watts, as this was a low-mass, fast mission that flew to Pluto in 9.5 years, with just one gravity assist at Jupiter. For an interstellar spacecraft there will be a much stronger need to minimize the instruments' masses. In the case of laser sailcraft weighing just a few tens of grammes or less, this would call for extreme measures, such as having entire sets of instruments on a single computer chip. This greatly limits what any one spacecraft can do, although it could be partly compensated by sending a swarm of spacecraft, as we will consider in section 16.3.

Inspired by the instruments on interplanetary spacecraft, let us now look at the classes of instruments an interstellar spacecraft might carry and what they can be used for.

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The scientific instruments on the Jupiter Icy Moons Explorer (JUICE). Credit: European Space Agency - ESA (acknowledgement: work performed by ATG under contract to ESA), ESA Standard License.

Fig. 16.1

Imaging. Ultaviolet/visible/near-infrared imaging is essential. Narrow-field imaging can be used to map the surface of planetary bodies in reflected starlight, with wide-field optical imaging used to look for new planets as well as moons and rings around planets. Both types of camera would also be used for navigation. It is common for planetary missions to use separate cameras for these two types of imaging because it allows each mode to be optimized separately. Mobile phones often have multiple cameras for the same reason, and because a single camera with optical zoom capability takes up more space. Cameras equipped with multiple filters enable broad-band spectral imaging, which helps to determine the composition and surface temperature of rocky bodies. A spacecraft making a rapid flyby may not want to waste time changing filters, so multiple cameras with different fixed filters might be used instead.

An example camera is Ralph on New Horizons. This is an off-axis three-mirror telescope with a 7.5 cm aperture, which uses a dichroic beamsplitter to send visible light and infrared light to different cameras. One of these is the Multispectral Visible Imaging Camera (MVIC) with a field of view of $5.7° \times 5.7°$ and four optical filters (400–975 nm), delivering $4''$ per pixel on the detector. The infrared channel is the Linear Etalon Imaging Spectral Array (LEISSA), which provides spectral maps in the range 1.25–2.50 μm at a resolution of $\delta\lambda/\lambda = 240$, and 550 in the range 2.10–2.25 μm, over a $0.9° \times 0.9°$ field of view at $12.8''$ per pixel. New Horizons also has a separate narrow-field camera called LORRI (the Long Range Reconnaissance Imager), a 20.8 cm camera with a $0.29° \times 0.20°$ field of view delivering $1''$ per pixel.

Planetary cameras often use methods from Earth remote sensing to construct larger images. A common approach is the 'push broom scanner', in which an image is built up in strips. This is often combined with a spectroscopic capability such that a spectrum is obtained in each pixel along the strip. This is how LEISSA is operated, for example, as does the High Resolution Stereo Camera (HRSC) onboard Mars Express, which achieved a ground

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resolution of 2.3 m when the spacecraft was at an altitude of 250 km. Whether such extensive high-resolution imaging could be transmitted back to the Earth from a distant star system is doubtful, however, for reasons discussed in chapter 15. But it might be used for limited areas of the surface of a planet identified by software on the spacecraft to be of particular interest, for example as possible sites of life.

Mid-infrared imaging is used to map low-temperature environments. The Europa Thermal Emission Imaging System (E-THEMIS) on Europa Clipper, for example, is a 6.45 cm aperture camera observing at 7–14 μm, 14–28 μm, and 28–80 μm, with a $6° \times 1°$ field of view. It aims to map the surface of Europa at 8 km resolution in order to identify sites of recent geological activity, and to determine surface temperatures over the range 70–230 K.

Spectroscopy. Ultraviolet/visible/near-infrared spectrometers are key to determining the composition of both solid surfaces and planetary atmospheres. Planetary spectroscopy at these wavelengths can use starlight reflected from a planet's surface – rock, ice, oceans, possibly even vegetation – or from an optically thick atmosphere, such as when investigating the spectral features on Saturn or Jupiter. The observation of starlight transmitted through a planet's atmosphere is a powerful means of investigating the physics and chemistry of the atmosphere. This is the same technique as used by telescopes on the Earth to investigate the atmosphere of an exoplanet as it transits across the surface of its host star (see section 2.3.1). However, that only works for the small fraction of systems in which the planet's orbit is seen almost exactly edge-on from the Earth. A telescope that flies to a non-edge-on planetary system can be manoeuvred to place the planet between it and the star, thereby inducing a transit, and so providing transmission spectroscopy we would otherwise never get from the Earth. Such a spacecraft could also spatially resolve different parts of the planet's limb during transit and – if it spent enough time in the star system – obtain transmission spectra at different times of the planet's year. Such observations could reveal a wealth of information about the planet's atmospheric composition and structure.

Different wavelengths reveal a range of information on different parts of an atmosphere or surface. The Visible and Infrared Mineralogical Mapping Spectrometer on Mars Express, for example, uses multiple gratings to observe in 352 spectral channels from 0.36 μm to 5.2 μm. The ultraviolet spectrograph Alice on New Horizons operates over 50–190 nm at 0.2 nm per pixel to investigate the temperature and compositional structure of Pluto's upper atmosphere, focusing on lines/bands of hydrogen, carbon monoxide, argon, neon, nitrogen, and methane. The JUICE spacecraft is equipped with a submillimetre spectrometer operating over the ranges 1080–1275 GHz and 530–600 GHz with a resolving power of 10^7 fed by a 30 cm dish. This will investigate the structure, composition, temperature, and dynamics of Jupiter's stratosphere and troposphere, as well as the surfaces and exospheres of the Galilean moons.

Particles. Imaging and spectroscopic instruments are photon detectors, and photons are essentially the only means astronomers currently have for investigating distant star systems.[1] One of the big advantages of in situ observations by a spacecraft is that massive particles can be directly detected.

The workhorse of particle investigations is the mass spectrometer. The name notwithstanding, this device often measures the mass-to-charge ratio of individual particles rather

[1] Astronomy is also done through the detection of high-energy particles (sometimes indirectly), and more recently gravitational waves, but the former cannot be used to tell us about specific individual stars or exoplanets, and the latter are currently limited to observing massive interacting bodies.

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than their masses. A typical spectrometer works by using one electric field to ionize neutral particles and another to accelerate them. A magnetic field is then used to deflect the ions through an angle via the Lorentz force. For known electric and magnetic field strengths, the angle of deflection is determined by the particle's mass-to-charge ratio m/q, which is inferred from where the particle lands on a detector. Observing a population of particles with different m/q ratios gives a spectrum showing the relative numbers of each type of particle. Another way of achieving this measurement is with a 'time-of-flight' mass spectrometer: ions are accelerated through a known potential U and so achieve an (unknown) kinetic energy $qU = (1/2)mv^2$. By measuring the time it takes the ion to travel a known distance (often by performing multiple bounces in a linear detector), we can determine the velocity v of the ion, and therefore m/q. One example of such an instrument is MASPEX (MAss Spectrometer for Planetary EXploration) on Europa Clipper. This achieves a mass resolution in excess of 17 000 by using thousands of bounces within the spectrometer, since the mass resolution equals the time resolution, which is proportional to the travel time. The goal of this spectrometer is to identify volatile compounds including water and organics in Europa's exosphere (and maybe also in plumes), and to associate them with geological surface features.

In some detectors, the kinetic energy of an ion can be determined from its impact in a solid state detector. As the incident ion passes through the silicon lattice of the detector, it is decelerated by ejecting electrons from the lattice. The current produced by these electrons is a measure of the ion's initial kinetic energy, $(1/2)mv^2$. Combining this with a time-of-flight measurement to determine v, the mass m and not just the mass-to-charge ratio is estimated. An example of such an instrument is the Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI) on New Horizons, which is sensitive to ions with energies in the range 1 keV to 1 MeV and achieves a mass resolution of 2–15 m_u. Another example is the Particle Environment Package (PEP) on JUICE, a suite of instruments that will measure the ions, electrons, and neutral atoms in Jupiter's magnetosphere and near its moons, with a broad range of energies from less than 0.001 eV to over 1000 MeV.

Particle detectors are not only useful in the vicinity of an exoplanet. They are also crucial for mapping out the interaction of the ISM with the stellar wind, the star's equivalents of our Sun's heliosphere (see section 12.2), and the interaction of this wind with a planet's atmosphere. The SWAP instrument on New Horizons was specifically designed to measure the interaction between the solar wind and ions created by atmospheric loss from Pluto. This provides an estimate of the rate of atmospheric loss from Pluto. It measures the energies and mass-to-charge ratio of charged particles in the solar wind with energies from 25 eV to 7.5 keV using a retarding potential analyzer and electrostatic analyzer.

Dust. Larger than individual atoms and molecules, dust particles reveal much about the surface composition of rocky planets. The SUrface Dust Analyzer (SUDA) on Europa Clipper analyses dust via a number of techniques. The flight time of incoming particles measured between a grid and a detector gives their velocities. A time-of-flight impact ionization mass spectrometer then ionizes a fraction of a dust particle through its high-velocity impact in the instrument, from which the mass-to-charge spectrum can be measured to determine the composition of the dust. Separately, this instrument measures the charge of dust particles as a way to estimate their size. New Horizons carries a dust counter to count the rate of dust particle impacts, and measured how this varied with distance to Pluto, thus mapping out the space density of the dust.

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How or whether these particle and dust instruments could work in a flyby mission when the spacecraft is moving at, say, $0.1\,c$ relative to the target star or planet is unclear. They would be most effective for an orbiting mission, also because that can get closer to the target and spend more time there.

Magnetic fields. The Earth and all of the gas giant planets in the solar system have strong magnetic fields. The magnetic field at Jupiter is so strong that interplanetary spacecraft need to take special measures to shield their electronics from high-energy particles accelerated by the field. Mercury has a very weak magnetic field, and Mars preserves remnants of past magnetic fields through magnetization of some of its surface.

J-MAG on JUICE is a magnetometer that will characterize Jupiter's magnetic field. This uses a fluxgate magnetometer, which works as follows. Two coils of wire are wrapped around a magnetically susceptible core. An alternating current is applied to one of these coils, which induces an alternating current in the other coil. In the absence of a magnetic field, these two currents are in phase. But when an external field magnetizes the core, this introduces a phase offset. The size of this offset is a measure of the external field strength and, by using multiple sensors with different orientations, the direction of the field can be determined.

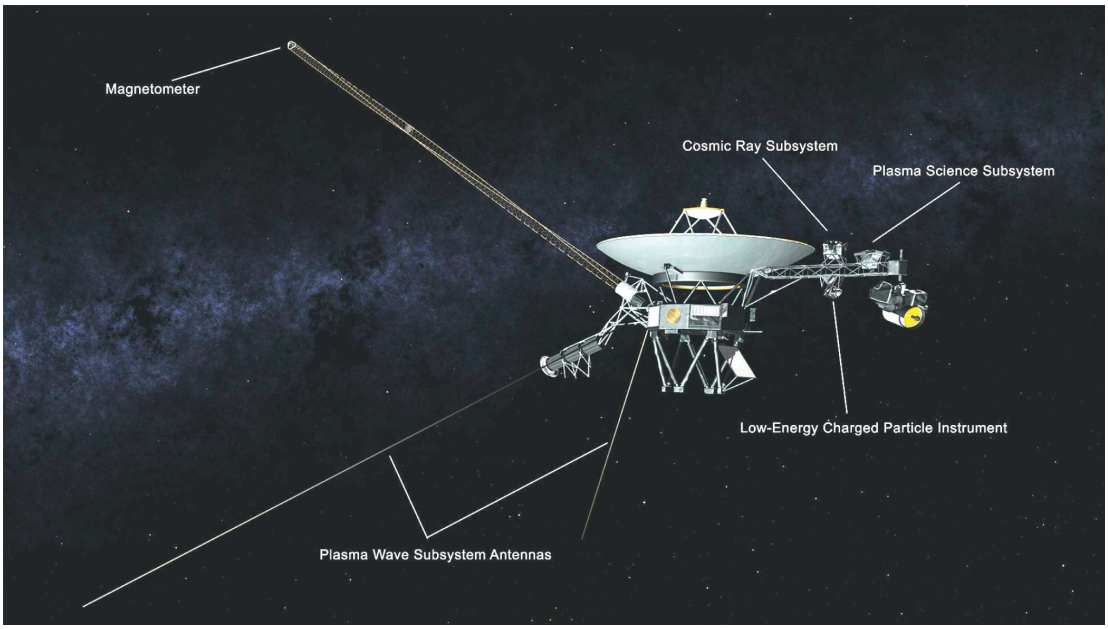
JUICE's magnetometer will also be used to investigate the suspected subsurface water oceans on the Galilean satellites Europa, Ganymede, and Callisto. While Ganymede has an intrinsic magnetic field, Europa and Callisto appear not to. However, time variations in Jupiter's field can induce currents in the oceans, which in turn can produce a measurable magnetic field. The strength of this field depends on the depth and salinity of the ocean and how this varies over the surface. Such experiments will be carried out by both JUICE and Europa Clipper. Magnetometers were flown on all the other missions to the outer planets too (Pioneer, Voyager, Galileo, Cassini, Juno). In all cases the instruments are mounted on booms to keep them away from the rest of the spacecraft to minimize magnetic interference with the instrument (figure 16.2).

The Radio & Plasma Wave Investigation (RPWI) instrument on JUICE can also measure magnetic fields, but uniquely it also measures electric fields. For this it uses Langmuir probes. These devices run an electric current along an electrode that is influenced by the temperature, density, and potential of the plasma that surrounds it. These devices may be sensitive enough to detect electric currents within Jupiter's moons.

Magnetic fields can also be explored indirectly using energetic neutral atoms (ENAs). Charged particles inside stellar or planetary magnetospheres are constrained to move on curved paths within the field, so cannot be collected by an external observer. However, if an ion collides with a neutral atom, it is possible for the ion to strip an electron off the neutral atom (a charge exchange collision). The ion retains most of its kinetic energy, but is now neutral, an ENA. As a result, this particle is no longer deflected by the magnetic field and escapes from the magnetosphere where it can be imaged. The Cassini spacecraft used an ENA imager to investigate a thermal ring current in Saturn, and JUICE is also be equipped with such an imager.

Radar. All of the instruments mentioned so far have been passive in the sense that they wait to measure whatever photon, particles, or fields they encounter. Radar ranging, in contrast, bounces electromagnetic pulses generated by the spacecraft off an object in order to measure the distance to it via the returned pulse's travel time. JUICE is equipped with two such instruments. GALA, the GAnymede Laser Altimeter, is a laser radar (a lidar), which will be used to study the shape of Ganymede at high spatial resolution. When JUICE passes

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The Voyager spacecraft indicating the location of some of the instruments. Credit: Courtesy NASA/JPL-Caltech. Fig. 16.2

within 200 km of the moon's surface, GALA will produce a spot size of 20 m on the surface, enabling it to map the surface with a vertical resolution of just 10 cm. In this way it is possible to map in detail surface features that might be caused by impacts, volcanism, or tidal forces. A similar instrument is in use on BepiColombo at Mercury. The brightness of the reflected beam can also be used to estimate the albedo and roughness of the surface.

A second instrument on JUICE called RIME – Radar for Icy Moon Exploration – is an ice-penetrating radar to study the subsurface structure of the moons. Using a 16 m antenna and operating at 9 MHz, this should be able to penetrate to a depth of 9 km and give a vertical resolution of 16 m. This will map the distribution of water in any subsurface ocean, as well as the variation in the ice thickness. A similar instrument is deployed on Europa Clipper and on the Mars Reconnaissance Orbiter.

Radar ranging requires the spacecraft to pass very close to the planet or moon, at altitudes of just hundreds of kilometres. This could be achievable for an interstellar spacecraft that goes into orbit around an exoplanet or exomoon, but is too risky, and of limited value, for a fast flyby.

Gravity. A perfectly spherical planet of uniform density has a gravitational field that varies only with altitude. Variations in the shape or density of a real planet, including from surface features such as mountains or deep oceans, means the gravitational field experienced by a low orbiting spacecraft varies as it passes over different parts of the planet. This in turn causes the position and velocity of the spacecraft to deviate from a Keplerian orbit.

Several interplanetary missions have made use of their radio communication link with the Earth to map the gravitational field of a planet in this way. By accurately measuring the line-of-slight velocity of the spacecraft via the Doppler shift of signals sent from an Earth-based transmitter, as well as variations in the signal travel time, perturbations of the orbit caused by variations in the planet's gravitational field can be measured. This enables some

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reconstruction of the mass distribution of the planet. Unfortunately, this kind of measurement will not be available to a single interstellar spacecraft. But one could imagine having two interstellar spacecraft, one remaining far from the planet and acting as the analogy of the Earth-based transmitter.

Not long after the first interplanetary missions in the early 1960s, landers were successfully deployed on the surface of planets, initially the Moon, Venus, Mars, and later Saturn's moon Titan. The first interstellar mission may just be a flyby, at a push perhaps an orbiting rendezvous mission. But one day orbiting spacecraft may be able to drop probes into the atmospheres of exoplanets, and eventually perhaps deploy landers or rovers (or submarines or aircraft). This would permit a much more detailed analysis of the atmosphere, geology, and oceans of exoplanets. I'll leave concepts for doing that to the imagination of the reader.

16.2 Power

Power is required onboard a spacecraft in the form of electricity for many functions, including operating scientific instruments, navigation, and communication. Manoeuvres to adjust the velocity or orientation of the spacecraft also require an energy source, even if they are not done with reaction thrusters but, for example, by changing the reflectivity of parts of a sail.

A spacecraft that is a rocket or Bussard ramjet could use some of its fuel as a source of electrical energy, for example to drive a generator in a thermal cycle. Some reactor-based fusion drives like those mentioned in section 8.7 are specifically intended to also provide electricity in this way. A nuclear reactor could even be added specifically for the purpose of generating electricity. Fission reactors have been launched into space, for example the experimental reactor SNAP-10a by the USA, which is defunct but still in orbit, or reactors on the 30 RORSAT spy satellites launched by the Soviet Union. But as nuclear reactors are massive, they are only an option for power generation on an otherwise massive interstellar spacecraft.

Photovoltaics for electricity generation from starlight are frequency used for satellites, increasingly also for deep space missions (e.g. JUICE and Europa Clipper). For a laser-propelled sail, one could even consider using the laser to beam energy. However, due to the enormous diffraction losses at large distances, this could only realistically be used when the spacecraft is still relatively close to the laser. When the spacecraft is far from either the Sun or the destination star, starlight is also far too weak to generate a useful amount of energy: 2 ly from the Sun – half way to Proxima Cen – the solar intensity is 10^{10} times lower than at the Earth, providing only $10^{-7}\,\mathrm{W\,m^{-2}}$. If the mission is designed to require very few operations during the cruise phase – perhaps with the spacecraft in hibernation, as is sometimes done for interstellar missions – then it might be able to rely on some other energy source in this phase, and only make use of starlight when it comes within a few astronomical units of the target star.

Other than photons, the only other source of external energy a spacecraft could rely on far from a star is the kinetic energy of interstellar particles. For a spacecraft travelling at a velocity v relative to the ISM, the power of particles stopped by the spacecraft is $P = (1/2)\dot{m}v^2$, where $\dot{m} = \rho A v$ is the mass flow rate, ρ is the space density of the particles, and A is the cross-sectional area of the spacecraft. Thus $P = (1/2)\rho A v^3$. If we consider just protons

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(of mass m_p) and adopt the local interstellar cloud space density of $n = 0.3 \times 10^6\,\mathrm{m}^{-3}$ ($= \rho/m_p$), then for a spacecraft travelling at $v = 0.1\,c$ the power per unit area is $P/A = (1/2)nm_pv^3 = 6.7\,\mathrm{W\,m}^{-2}$. This power would have to be converted to electricity somehow, and this would be much less than 100% efficient. As the colliding particles heat the front of the spacecraft, it might be possible to exploit the temperature gradient along the spacecraft to extract this energy as electricity via the thermoelectric effect (discussed below). But to extract several watts of power in this way we would need a significant cross-sectional area. Sails have large areas, but they would also need devices to extract the power, which could add significant mass.

If we cannot use external sources of power, the spacecraft will need an internal one. Options include batteries, capacitors, fuel cells, and radioisotope thermoelectric generators, each of which we will now consider.

Batteries. Current commercial lithium-ion batteries are able to store about $1\,\mathrm{MJ\,kg}^{-1}$ or $300\,\mathrm{Wh\,kg}^{-1}$ of energy. The best achieved so far have a capacity of around $2.5\,\mathrm{MJ\,kg}^{-1}$. Even with a low payload power of 1 W on average, one kilogramme of such a battery could provide power for only one month. Larger masses of battery could be used, but as we shall see, other options have higher energy densities. Batteries also drain with time, lowering their stored energy. As the sole power source for a multi-decade mission, even if the payload is switched off most of the time, batteries do not look like a good option.

Capacitors. A capacitor also stores electrical energy. Electrolytic capacitors have very low energy densities, however, not much more than about $0.001\,\mathrm{MJ\,kg}^{-1}$ and with very short drain times (days at room temperature). More recent electrostatic double-layer capacitors can increase this to up to $0.7\,\mathrm{MJ\,kg}^{-1}$, but this is still less than batteries. The one advantage of batteries and capacitors, however, is that they can be very small, with little mass overhead for the structure (unlike for fuel cells, heat engines, etc.). So if only very small energies are required, batteries and capacitors may have a niche. They may also be required to regulate power and serve as short-term backups.

Fuel cells. A fuel cell extracts an electric current from the exothermic reaction of combining hydrogen with oxygen. After molecular hydrogen is ionized at an anode, the protons flow through an electrolyte to combine with the electrons (which flow via a separate circuit) and oxygen at the cathode, forming water. The energy density of hydrogen, $120\,\mathrm{MJ\,kg}^{-1}$, is much higher than that of a battery, but a spacecraft must of course also carry the oxygen, which increases the mass by a factor of nine, reducing the energy density to $13\,\mathrm{MJ\,kg}^{-1}$. Including the mass of the cell itself reduces this further. This is still superior to batteries for all but the smallest amounts of energy (when the mass of the empty cell would dominate). Fuel cells were used as one of the onboard power sources on Apollo and the Space Shuttle, with average powers of 1.5 kW and 7 kW, respectively.

Radioisotope thermoelectric generators (RTGs). One of the main sources of power for deep space missions has been the radioisotope thermoelectric generator (figure 16.3). This extracts electrical energy from the heat produced by the radioactive decay of an isotope, usually plutonium.

A single atom of plutonium-238 decays to uranium-234 by alpha decay, releasing 5.6 MeV energy, most of which goes into the alpha particle. Together with the rate of decay of plutonium-238 (the half-life is 87.8 years), we can compute that this corresponds to a power of $570\,\mathrm{W\,kg}^{-1}$. This heat source, when connected to a heat sink such as a radiator in space, creates a temperature gradient. Electricity can be extracted from this gradient via the Seebeck

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Fig. 16.3 An RTG on the New Horizons spacecraft at Kennedy Space Center shortly before launch. The RTG is the black cylinder on the left. It is 1.14 m long and covered with cooling fins. Credit: NASA.

effect: when two ends of a conductor are maintained at different temperatures, a potential difference between the two ends is generated (due to differences in the energy level occupation in the conductor, together with electron diffusion). The size of the potential difference, known as the Seebeck coefficient, depends on the material, and varies from around $-100\,\mu\mathrm{V\,K^{-1}}$ to $+1000\,\mu\mathrm{V\,K^{-1}}$. Connecting two different materials with different Seebeck coefficients in a circuit allows a current to flow, from which we can extract electrical energy. The energy comes from the heat source used to maintain the temperature difference. The Seebeck effect is widely used, for example in power stations, wrist watches, and oven fans, and is the method conventionally used in RTGs to generate electrical energy.

RTGs were used in the Pioneer and Voyager spacecraft, New Horizons, as well as the Mars landers and rovers. The Cassini mission to Saturn used 33 kg of plutonium that produced 885 W of electrical power at the beginning of its 20-year mission. This corresponds to an electrical power of $27\,\mathrm{W\,kg^{-1}}$, a factor of 20 lower than the heat power. This reflects the inefficiency of the energy conversion. Once we also take into account the mass of the entire device, the initial power rating is only about $5\,\mathrm{W\,kg^{-1}}$. This power decreases with time t as $\exp(-t/\tau)$, where the half-life is $\tau \ln 2$. After 50 years of operation, the power from the RTG drops to 67% of its initial value. In this time it has delivered $6.5\,\mathrm{GJ\,kg^{-1}}$ of energy, which is orders of magnitudes more than batteries or fuel cells.

Given its long half-life, plutonium-238 is suited well for interplanetary missions, and would also be suitable for interstellar missions with durations less than about 100 years. Plutonium-238 also has a very low gamma-ray and neutron flux (from spontaneous fission), so the shielding requirements are minimal, much less than for other candidate isotopes. It is typically supplied in the form of plutonium dioxide (PuO_2), which has a high melting temperature. Plutonium-238 itself is usually generated in fission reactors by irradiating

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neptunium-237 with neutrons, neptunium-237 itself being generated through a series of neutron reactions and beta decay from uranium-235.

A recent problem with RTGs is the limited availability of plutonium-238, as production has decreased significantly since the 1980s. Partly for this reason, other radioactive sources are being investigated for use in RTGs. Polonium-210 alpha decays to lead-206, releasing 5.4 MeV. This is similar to the energy released in a plutonium-238 alpha decay. But with a much shorter half-life of 138 days, polonium-210 delivers a much higher power of 144 kW kg^{-1}. However, this short half-life renders it useless for an interstellar mission. Strontium-90, which beta decays via yttrium-90 to zirconium-90, also has a similar power output to plutonium-238, but a half-life of 28.9 years. For long missions, americium-241, which alpha decays to neptunium-237 with a half-life of 433 years, is an attractive option, although its power density is four times less than that of plutonium-238.

There are ways other than the Seebeck effect to extract electrical energy from an RTG. By using the thermodynamic Stirling cycle, about four times as much electrical power can be extracted per kilogramme of plutonium than has been achieved so far in space missions. A disadvantage of this, however, is that unlike a traditional RTG, which has no moving parts, the heat engine involves continuous movement and a working fluid. This generates vibrations and increases the risk of mechanical failure. One prototype developed by NASA is the Advanced Stirling Radioisotope Generator. This uses 1.2 kg of plutonium-238 to generate 130 W of electrical power (initially) in a unit that weighs 32 kg.

16.3 Relays and swarms

Developing the first interstellar spacecraft will be expensive. There will be significant costs in research, development, production, and operations. How these costs are distributed depends on which technologies are developed, not least which propulsion method is used. As a single fusion engine is likely to be massive and expensive, the spacecraft itself will be massive and the cost of producing one spacecraft relatively high. With a laser sail, in contrast, much of the construction cost will be in the laser array, which will remain at the Earth and can be reused many times. The production cost of an individual sailcraft is probably small in comparison.

For laser sailcraft at least, it therefore makes economic sense to build and send many spacecraft. Moreover, given that the sailcraft may be very light (grammes) and therefore only able to carry a very limited set of instruments, the complete set of instruments required to fulfil the scientific objectives could be spread across multiple sailcraft. This makes even more sense if the spacecraft is to make a fast flyby. At 10% the speed of light, the spacecraft traverses 1 au in just over an hour, with the result that one camera on one spacecraft could not gather much data. An individual spacecraft would also fly past just one side of a star or planet, whereas multiple spacecraft could be navigated to view the target from multiple perspectives.

Single point failures would destroy a spacecraft. Examples include a large dust grain, or critical hardware damage caused by cosmic rays. Sending multiple spacecraft offers more security against such catastrophic failure, to the extent that one could even anticipate losing some fraction of the spacecraft. We could therefore build in across-spacecraft redundancy, just as now there is usually within-spacecraft redundancy for critical systems.

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The idea of sending multiple spacecraft is not necessarily limited to laser sails or to flyby missions, however. As soon as the marginal cost of producing and operating a spacecraft is small compared to the research, development, and other set-up costs, it makes sense to send multiple spacecraft.

Given the unknowns of interstellar travel, there is some advantage in sending multiple spacecraft consecutively rather than simultaneously. This way, information gathered by the first spacecraft could be used to inform the later ones. For example, if an early spacecraft identifies a previously undetected planet or moon, one of the later spacecraft could modify its course to fly closer to that. Or if one of the first spacecraft fails to make a high-priority observation for some reason, such as an instrument failure or course error, a later spacecraft could make it instead. To do this, the spacecraft need to communicate with one another. This complicates their communication systems, and also implies that they cannot be too far from one another (think Friis transmission equation), which may limit the extent of possible course corrections. It also assumes that the spacecraft are equipped with intelligent software, but this, at least, is one of the areas of technological development we can be fairly confident to attain (see section 16.4).

The frequency and timing of launches of multiple spacecraft from the Earth (more likely, Earth's orbit) could depend on a number of factors. Laser-propelled sails require use of the laser for an extended period. As we saw in chapter 11, some very low-mass sail missions have beam times of just minutes. But even those require enormous amounts of energy, which will probably have to be generated over much longer periods and stored. A launch rate of one spacecraft per day may be a reasonable highest frequency estimate. For a cruising speed of $0.1\,c$, this corresponds to a distance of 17 au between them. Of course, the spacecraft may not all receive exactly the same amount of energy and so not travel at the same speed, giving rise to a possibly uncontrollable spread in their arrival times. But if the laser could be operated for a year, 365 spacecraft could be sent, leading to high levels of redundancy and/or payload distribution.

Sending multiple spacecraft has implications for the ground segment, because ground-based telescopes are needed to receive the data from all of them ('ground' here includes Earth's orbit or the Moon). Given that flyby spacecraft will store their data and send it back over a duration that is much longer than their encounter durations, this means receiving data from multiple spacecraft simultaneously in the same telescopes. The signal coding and modulation discussed in chapter 15 will have to be designed to prevent interference between the signals, and allow us to distinguish between the spacecraft.

If the spacecraft are launched over a time span that is similar to their journey time, they could act as a relay of the data obtained by the currently encountering spacecraft. This could result in a larger data rate for a given transmitter power and area. Suppose that the ratio of the area of an Earth-based receiver to the spacecraft receiver is f ($f \gg 1$), and that each spacecraft receiver has the same area as its transmitter. All other things being equal, the data rate for spacecraft-to-spacecraft communication is then f times smaller than for spacecraft-to-Earth communication (from the Friis transmission equation in section 15.2). But in a relay, the individual spacecraft are much closer to one another than the encountering spacecraft is to the Earth, let's say by a factor of n, which is also the number of equally spaced spacecraft between the Earth and the target star. Considering again the Friis transmission equation, and neglecting other losses, it follows that when $n^2 > f$, a relay system delivers a higher data rate than a direct transmission. If the Earth-based receiver is an array of 100 telescopes

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each of 10 m diameter, and the spacecraft have 1 m diameter mirrors, then $f = 10^4$. In that case we would need more than $n = 100$ spacecraft for the relay to be advantageous. In reality we would need closer spacings, and so more spacecraft, because every reception and transmission in the relay adds instrument noise that we only have once in direct transmission. Furthermore, the benefit of the relay diminishes with time when the later spacecraft arrive at the target and lack the full set of relay spacecraft behind them. On the other hand, if the last n spacecraft are only used for relaying signals, then we no longer need a large receiver on the Earth, but just one equal to the size of the spacecraft receiver, because that is already the limiting factor in the relay.

The alternative to a relay of multiple spacecraft is to send them in a swarm, such that they arrive over a time period that is not much more than their encounter duration. Even when spacecraft are launched consecutively, for example by a single laser array, this could be achieved by giving them different velocities. There are several benefits of a swarm. First, it allows simultaneous observations of the same object from different viewing angles; this could be particularly interesting for transient phenomena. Second, it allows more active observations, in which one spacecraft transmits a signal that is received by another, for example in radar ranging or atmospheric transmission spectroscopy (see section 16.1). Third, the spacecraft could even together synthesize a large telescope aperture array for transmitting information back to the Earth. This gives much smaller diffraction losses than any single spacecraft transmitter acting alone. This could be achieved – in the radio at least – with a phased array antenna, mentioned in section 15.8.3.

16.4 Autonomous control

The multi-year round-trip communication time to the nearest stars implies that interstellar spacecraft have to operate autonomously for most of their mission. Intelligent software is therefore essential for many tasks that require obtaining and interpreting data, making a decision, and taking a course of action. These tasks include:

- navigation measurements and corresponding adjustments in spacecraft course and orientation;
- identifying targets, in particular planets and moons, in the target star system;
- switching instruments on and off, not only at the target star system but also at critical phases during the mission, such as crossing the Sun's heliopause;
- operating instruments, including tracking targets during a rapid flyby;
- prioritizing observations during critical mission phases in the face of limited observation time and power;
- reconfiguring computer hardware and modifying software as the result of damage, for example if some processors or memory are damaged by cosmic rays;
- prioritizing the storage and transmission of scientific data. The spacecraft may collect more data than it has the capacity to store or transmit back to the Earth (this is already the case in some astronomy missions). It will therefore need to assess the quality and the importance of the data. The channel capacity of the downlink may also be different from expectations (e.g. due to a damaged antenna or reduced power), which would also require a modification of the nominal data plan;

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- communicating and coordinating with other spacecraft in a relay or swarm. Earlier-arriving spacecraft may fail to achieve specific goals, or may identify new objects worthy of investigation, requiring later spacecraft to reassess their goals and capabilities. If spacecraft are operating in concert, such as for radar or transmission spectroscopy measurements, then coordination is critical and complicated.

Interplanetary spacecraft have achieved increasing degrees of autonomy in recent years. Comet and asteroid intercept missions like Deep Impact have operated autonomously for hours at a time during their short mission-critical encounters. Other missions such as Rosetta, OSIRIS-Rex, and Hayabusa, which have spent extended periods of time at a comet or asteroid, also operated autonomously during their investigations, in each case bringing the spacecraft or a separate lander into contact with the body. Mars and Moon landers are also able to control their descent autonomously in response to real-time data on velocity and altitude, as well as the identification of unsuitable landing locations (rocks, craters). Generations of Mars rovers have used increasingly sophisticated algorithms to navigate autonomously over the surface of Mars, avoiding obstacles without intervention from Earth-based controllers.

As it will be difficult to pre-program software to allow for all possibilities, and as software updates will be difficult to perform, spacecraft will probably need to rely on artificial intelligence (AI) to some degree. Although we have seen huge increases in the performance of AI systems over the past few years, these require vast data sets to train. Such data do not exist for interstellar travel, so they would have to be simulated in some way. Trained AI systems often have large storage demands, and although computer memory is compact and light, the chips used on spacecraft must include sufficient shielding against ionizing radiation. Sophisticated computing systems may also require considerable power, and therefore cooling, both of which add mass to the spacecraft.

16.5 Summary

Interstellar spacecraft should carry a number of different scientific instruments to explore their target star systems. Many of these will be similar in concept to those used on planetary exploration missions in our solar system. This includes imagers, spectrometers, magnetometers, and particle and dust analyzers. As mass is even more critical for an interstellar mission, instruments will have to be optimized and miniaturized. An orbiting mission will allow much more science to be done with more sophisticated instruments than a fast flyby.

When the marginal cost of launching a single spacecraft is small compared to the total mission cost, it makes economic sense to launch multiple spacecraft. This allows the scientific instruments to be spread across multiple spacecraft or provides redundancy against the failure of some spacecraft. Multiple spacecraft launched near-simultaneously in a swarm can act together to increase the science return. When launched consecutively, they could instead adapt to the achievements of earlier spacecraft, and even act as a relay for communication back to Earth.

One of the biggest challenges of interstellar travel is achieving sufficient onboard power. Batteries, capacitors, and fuel cells are too massive or have too low energy densities for them

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to be a useful option. For a nuclear rocket it would be feasible to carry relatively massive power systems, such as a nuclear reactor or an RTG. Perhaps RTGs can be miniaturized, but currently they and reactors are far too massive to be carried by realistic laser sails. Higher-mass lightsails could be equipped with wafer photovoltaics, but more than a few astronomical units from a star the starlight is too weak for these to be effective. Whether sailcraft could survive most of their journey in hibernation with no power is unclear. In principle, power could be generated from ions in the ISM incident on the high-speed spacecraft, but extracting this requires devices that add mass.

16.6 Exercises

1. Go through the calculations in section 16.2 for the RTG to compute the total energy delivered per unit mass, but now after 200 years.
2. How is the operation of the instruments discussed in this chapter affected when used on a spacecraft passing the target star and planet at a relative speed of 0.1 c?

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