# 9

# Exploring and Developing Space by Sailcraft

Sailcraft offer unique opportunities to space mission planners. Some of these possibilities will be exploited in the near future, others within a few decades and some in the more distant future. We consider near-term mission possibilities first.

## NEAR-TERM (2015–2025) SAILCRAFT MISSION OPTIONS

The earliest operational solar sail missions will demonstrate the utility of this space-propulsion technique. Most likely, these missions will be directed toward destinations within a few million kilometers of Earth.

### Solar Storm Monitoring

This section explains in a simple way what a solar storm is, its consequences on some human activities and how astronautical experts think of mitigating serious troubles in a near future.

Most are not aware that the “good old stable Sun” is not so stable. In addition to the usual solar wind (Chap. 6), several times a year (and more frequently during the peak of its 11-year cycle), the Sun emits Earth-sized bursts of high energy plasma (a mixture of charged particles; typically protons, electrons and alpha particles) into space. These enormous plasma bursts, often referred to as “solar proton events” by physicists and “space storms” by the media, speed outward from the Sun at 250 to 1,000 km/s.[1] Eventually, some cross the orbit of Earth and wreak havoc with Earth-orbiting spacecraft. We don’t directly notice their impact, unless we happen to be living near the North or South Pole, in which case we would see an increase in auroral activity as some of the radiation penetrates the ionosphere and gets trapped along the planet’s north or south magnetic field lines.

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[1] There are two distinct flows of solar wind: the slow wind (with a mean speed of about 400 km/s) and the so-named *fast streams* (with a mean speed of about 800 km/s), which originate at different latitudes on the solar corona.

G. Vulpetti et al., *Solar Sails*, Springer Praxis Books,
DOI 10.1007/978-1-4939-0941-4_9

The resulting auroral glow, called the "northern lights," are often spectacular as the ions spiral along the magnetic field lines deep into the atmosphere, ionizing atmospheric oxygen and causing it to glow a brilliant green. A brilliant light show, but not a threat to human life and activity, correct? Well, this would have been correct if stated 100 years ago, but not today, in our age of dependence on electricity and on spacecraft for communication, weather forecasting and national defense. Spacecraft using solar sails will help us mitigate the risks posed by such storms.

When a space storm reaches Earth, interesting things happen to the protective bubble around our planet called the **magnetosphere**. To understand this and how it is germane to our civilization, requires first some understanding of the magnetosphere itself. Recall that all magnets have both a north and a south pole, between which is generated a magnetic field. You cannot directly see this field, but you can observe its effects. For example, if you have two bar magnets and attempt to touch their two north poles together, you feel a repulsive force. Conversely, if you take the north pole of one magnet and attempt to gently touch it to the south pole of another, you have the opposite problem. They will attract each other, and you must exert force to keep them from coming together too quickly. Any magnet generates a magnetic field; it is through this field that adjacent magnets interact, and they interact by attracting or repelling each other, depending on their orientation.

Earth itself generates the equivalent of a bar magnet somewhere in its interior, with the magnetic north pole being near the "top" (or north spin axis point on the planet) and the south pole on the "bottom." (In actuality, Earth's spin axis "north pole" and its magnetic north pole do not physically coincide. They are offset by approximately 11°.)

The next piece of the puzzle that must be understood in order to explain the interaction of a space storm with Earth is the **ionosphere**. The ionosphere is a region of the atmosphere that begins at an altitude of roughly 80 km from the surface. The atmospheric density has decreased at this altitude to the point where sunlight strips electrons from their parent atoms (typically oxygen) and they exist for extended periods of time as "free electrons" before they collide and recombine with some other atom. The flows of ionized oxygen (and other) atoms and these free electrons form plasma.

Another interesting property of charged particles is that they are affected by both electric and magnetic fields. A charged particle, like an electron, in the presence of a magnetic field will experience a force that causes it to move in a direction perpendicular to both its initial direction of motion and to the magnetic field lines. The magnetic field exerts a force on the ions and electrons in the plasma that results in them spiraling along Earth's magnetic field lines, bouncing back and forth between the North Pole and the South Pole.

Earth's magnetic field, second only to Jupiter in strength within the planets of the solar system, acts as a shield against these intense solar storms, which repeatedly diffuse in the solar system. Without it, life on Earth might not be possible—and it certainly would not be what we see today. High levels of radiation can certainly harm living things, but it also damages or disrupts the function of electronic systems. Complex systems, such as those found in spacecraft, are especially vulnerable. Satellites launched into space are designed to minimize the effects of these storms and generally speaking, do so successfully. The easiest way to protect against the harmful effects of the ions in the solar storm is by adding shielding mass. Mass, simply put, blocks the ions from reaching whatever is behind it. Unfortunately, with launch costs near 15,000 USD/kg (7,000 USD per pound), most satellite users don't want to spend a lot of money adding mass to whatever it is they are launching into space. They instead prefer to either save the money or use whatever extra mass they have available to add more payload (whether it be transponders or science instruments), thus increasing either their revenue or overall science return.

Unless the owners and operators of Earth-orbiting spacecraft do something to mitigate the effects of these storms, damage will occur. The loss of a satellite might seem at first to be an esoteric risk that affects “someone else.” Instead, imagine the loss of weather satellite coverage for an extended period of time, including the hurricane season; the ability to accurately predict the location of landfall for a category 4 or 5 hurricane declines to the point that major population centers must be evacuated just because we don’t precisely know the track of any particular storm and people may be in its path.

Companies and whole industries use the global positioning system (GPS) and other satellite assets to accurately manage their inventories and track shipments. Corporate managers plan their business strategy and make decisions based on where certain products or materials are located at any given time. With a sudden loss in this capability, millions or even billions of dollars might be jeopardized.

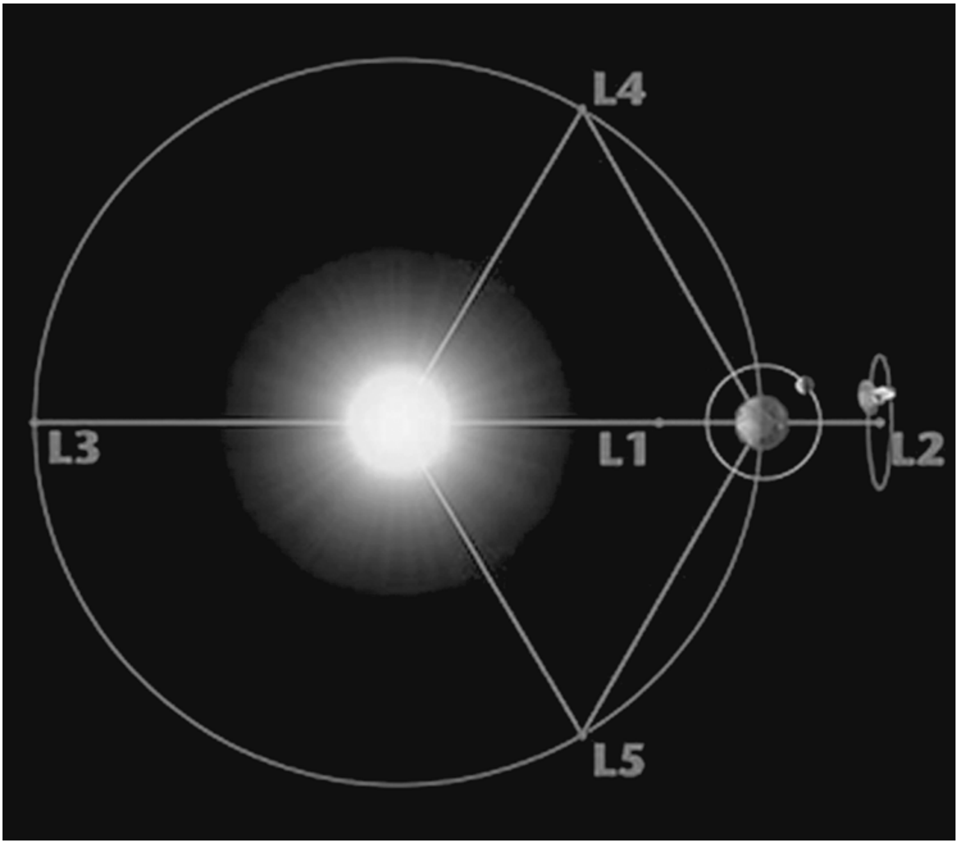
Cable television, now estimated to be in 68 % of television-equipped US households, is also at risk. After all, the cable only carries the television signal from your local cable company to your living room. The cable company gets the television signals from satellites located about 36,000 km above the equator. If the satellites go out, the cable companies go out of business.

Perhaps most importantly, the loss of the US’s military and spy satellites would leave whole countries vulnerable to a surprise attack. Knowing that the spy satellite infrastructure is “down” might be a very tempting opportunity for an adversary to take advantage of. (Of course, this also holds for other countries in the world.)

There are other, more down-to-earth impacts spawned by these storms, especially for those living at northern latitudes. Recall that charged particles moving through a magnetic field will experience force acting upon them. So also will a moving magnetic field induce an electric current in a wire. Electrical utility wires (particularly those hanging from telephone poles at northern latitudes) will feel the effects of solar storms as Earth’s magnetic field is compressed, varying in intensity with time. This changing magnetic field induces current flow in the wires, creating spurious currents that knock out transformers and otherwise disrupt or shut down the transmission of electrical power. This is a real effect and it has happened.

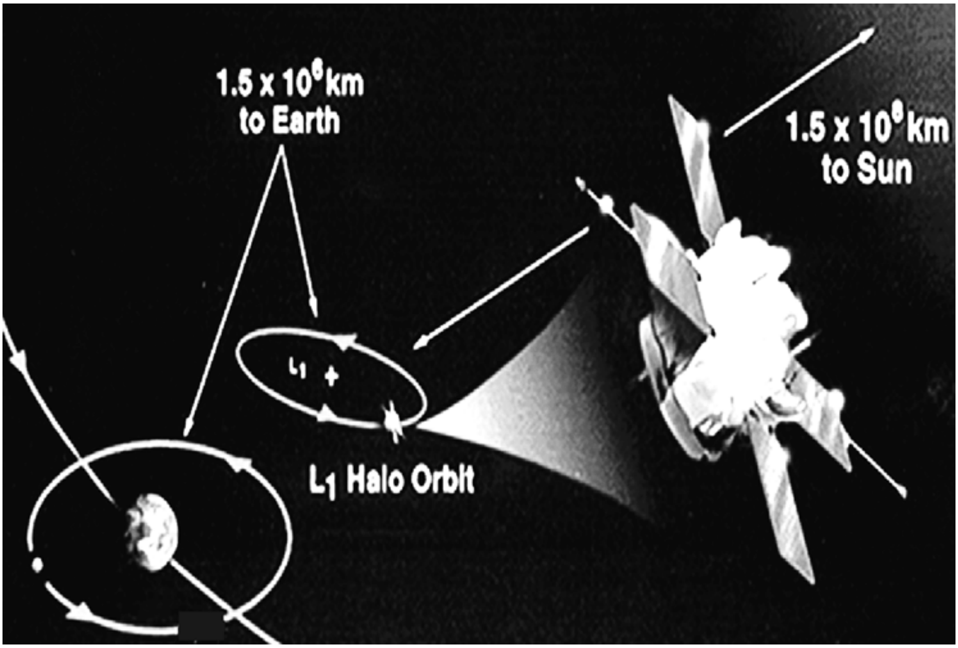
Fortunately, in addition to adding lots of mass to the spacecraft, there are two other ways to mitigate the effects of these storms, and both require some sort of advanced warning of an impending storm. One is to turn off particularly vulnerable spacecraft systems when the worst of the storm arrives, and power back up after the storm is over. The other would be to reorient the spacecraft so as to maximize any onboard spacecraft mass between the most vulnerable systems and the ionizing radiation in the plasma for the duration of the storm.

To provide at least some warning of impending solar storms, the US National Oceanic and Atmospheric Administration (NOAA) and NASA placed the Advanced Composition Explorer (ACE) spacecraft at one of the so-called Earth/Sun Lagrange points. In the seventeenth century, Italian mathematician Giuseppe-Luigi Lagrange (who worked in France for 27 years) discovered that there exist regions in space where the gravitational



9.1 The Lagrange points of the Sun-Earth system

attraction of the Sun and Earth mostly cancel each other out, meaning that a spacecraft placed in one of these regions will likely remain there unless acted upon by some outside force. These regions (around the so-called *libration* or L-points) are not 100 % gravity or disturbance free, so some spacecraft propulsion is required to remain within them (Fig. 9.1). The fuel required there, however, is much less than would be required should these regions not exist. The ACE spacecraft is located at the Earth/Sun L1 point (1.5 million km from Earth) and monitors the Sun for solar-proton events (Fig. 9.2). It detects such an event when the light from a solar flare associated with the event strikes its detectors; the spacecraft then sends a radio signal back to Earth. The radio transmission signaling the impending storm reaches Earth about 1 h before the ionizing radiation because light travels faster in the vacuum of space than do the charged particles in the storm. Unfortunately, 1 h is not much time, in general, even considering the very high number of aircraft in flight and the complexities of the various human activities that could be seriously degraded or halted by solar storms.



9.2 The ACE spacecraft around L1

Here's where the sail comes in. The next generation of L1-based solar observatories will use conventional rockets to escape Earth's influence and decelerate at L1. Then, the craft will deploy a modest solar sail, perhaps 50–100 m in diameter. Applied to correct for the various gravitational influences working to drag the solar monitor off station, the sail could maintain spacecraft position with a great reduction in onboard fuel requirements, which translates into longer spacecraft operational lifetime and lower costs.

Even better, a sailcraft can be positioned in a direct line between the Sun and Earth, remaining in this otherwise propulsive-intense location, and can be available to provide earlier warning of impending storms. The ship must thrust continuously to remain on station—a task ideal for a solar sail.

NASA is considering a mission using a solar sail to either replace the ACE spacecraft or act as a complement to its replacement. The potential mission has been called many names, from "Geostorm" to its current incarnation, "Heliostorm." Trade studies to determine the optimal science instrument complement, spacecraft and solar sail propulsion system characteristics are ongoing, and will likely continue until the mission is approved for flight. An early Heliostorm concept would use a square sail, 70 m on each edge, with a total mass of <200 kg to accomplish the mission goals. It would be launched from Earth in a relatively small rocket, such as a Pegasus or Falcon, and propelled to 0.98 astronomical units (AU) by a conventional chemical rocket. The sail would then deploy and operations commence.

An advanced version of the Heliostorm concept (based on advanced technology) would consist of a sailcraft with a total mass of 300 kg and a circular sail 230 m in radius. Such a spacecraft could orbit the Sun stably at 0.70 AU (never being captured by Venus) in the ecliptic plane with a period of exactly 1 year. Once put 0.30 AU from the Earth sunward, its mean position with respect to Earth would not change, and the space-storm warning time would range from 16 to 31 h. (A technical explanation of this mission concept can be found in Chap. 17.) Such time would be enough even for astronauts who will be working on the Moon, far from their lunar base.

## Pole Sitters

Another space mission of interest that could be implemented in the near term is the terrestrial pole sitter. Using the thrust on a sail provided by sunlight to balance Earth's gravitational attraction, a pole sitter is just that—a sail-propelled spacecraft that appears to "sit" above one of the Earth's poles. This is a high-latitude analogue to the geosynchronous position of most communication satellites, which are permanently stationed 35,786 km above the equator. The period of such an orbit is exactly one Earth rotation period (about 86,164 s) and the satellite will apparently remain stationary above the same location on Earth's surface and serve as a convenient target for radio beams.

A terrestrial pole sitter would be situated in the sky as near to the pole star's location as possible. Rather than rotating at the same angular velocity as Earth's surface, it would have a relatively constant location on the celestial sphere. Thus, designers of telecommunication, Earth-resource, navigation and weather satellites designed to serve high-latitude users cannot use this convenient orbit since high-latitude ground stations find geosynchronous satellites to be below or near their horizon.

The way that part of the solar wind reaches Earth's upper atmosphere is somewhat complicated and not yet completely explained. A significant step in our understanding of the solar wind interaction with Earth's magnetosphere has occurred in recent years based on key observations from a number of modern satellites designed for such an aim—the missions IMAGE (NASA) and CLUSTER (ESA). For the first time, there has been the observational evidence of something conjectured some decades ago: the magnetic reconnection. The solar wind carries the lines of the heliospheric magnetic field (HMF); when the HMF direction is opposite to that of the field of Earth's *magnetopause* (the magnetosphere boundary that acts as our magnetic shield), the lines of the two magnetic fields can first break and then reconnect with each other in such a way that one or more enormous "cracks" (typically larger than Earth) are produced in the magnetopause. The solar wind now slides along the terrestrial magnetic lines down to the ionosphere. In going down, the plasma tube area decreases to sizes typically equivalent to Japan. The unexpected feature of such magnetopause cracks is that they can stay open for many hours, thus provoking *severe space storms.*

Although high-latitude pole sitters are certainly possible, they will have certain annoying consequences for telecommunication customers. Studies indicate that solar sail pole sitters will function best if situated at the Moon's distance or beyond. This greater distance would introduce a longer time delay in telephone calls via pole-sitter spacecraft. This will not please all customers!

The ability to hover over a single area of Earth would be highly desirable for those monitoring the environment. Instruments placed on such craft would be able to continuously monitor local weather and environmental conditions. Military users would also benefit from the ability to continuously observe the activities of a potential adversary.

## Near Earth Asteroid Reconnaissance

The catalog of known near-Earth asteroids (NEA) grows yearly as newly discovered asteroids are added to the database. As of August 2012, there are more than 800 objects with a diameter greater than 1 km in the database. These objects are of interest for a variety of reasons. Some have the potential to strike the Earth at some point in the future. Others are rich in minerals and elements that are in short supply on Earth and, because of their composition, may be mined in the future. Many represent the best known record of what the early solar system may have been like and are interesting from just the science that can be learned from them. Still others are potential destinations for future human exploration and therefore we need to robot-reconnoiter them prior to sending humans.

Using a solar sail propelled spacecraft to survey NEAs is attractive from several points of view. First, NEAs are, by definition, near the Sun and therefore there is sufficient sunlight to make solar sail propulsion possible. Next, with a sailcraft, there are no expendables and therefore there is no intrinsic reason a sailcraft cannot visit multiple NEAs sequentially until something other than the propulsion system breaks down and stops functioning. Finally, the large DV produced by a sail allows the sailcraft to rendezvous with a NEA, matching velocity with the object and observing it close up for an extended period of time. With a conventional chemical or electric propulsion system, it would be difficult to flyby more than two NEAs, and almost impossible to rendezvous with them—the propulsive requirements are just too high.

The advent of solar sail technology, simultaneously with the emergence of cubesats (small spacecraft only a few tens of centimeters long and typically weighing between 3 and 12 kg), offers the possibility of sending out a swarm of 100 $m^2$ sailcraft to visit multiple NEAs, thereby characterizing these important residents of space near our Earth.

## Magnetospheric Constellations

An additional near-term, near-Earth possibility is to launch a number of mini-solar sails (not the micro-sails introduced in Chap. 7, but decidedly larger), or “solar kites” aboard the same rocket. Equipped only with miniaturized communications and navigation gear and instruments to monitor space radiation and fields, these craft could use solar sails to cruise through Earth’s magnetosphere between, say, 2,000–50,000 km above Earth’s surface. This scientific “constellation” would yield real time and synoptic data about variations in Earth’s magnetic field and radiation belts.

## Target-Variable Magnetospheric Missions

With regard to deeper scientific exploration of Earth’s magnetosphere and, at the same time, to experiment with solar sail technology and study its problems, the European

Space Agency considered a mission named Geosail. In reality, the primary goal of Geosail would have been the full demonstration of solar sailing, though the sail area had to amount to about 1,900 $m^2$ (2.5 times the area of a baseball diamond). Full demonstration means mainly sail packing, in-orbit sail deployment, sail attitude acquisition and control, sail-state monitoring, using solar pressure acceleration for continuous orbit change, sail attitude maneuvers, sail detachment, and even (indirectly) observing sail's materials degradation. The mean orbit of Geosail would have been well beyond the geostationary orbit, between 70,000 and 150,000 km; its perigee should touch or cross the near magnetopause, whereas its apogee should dive in the magneto-tail. Such an orbit should be high *variable,* not only because of the gravitational perturbations caused by the Moon and the Sun, but mainly because the magnetopause continuously changes also in orientation. As a point of fact, the solar wind moves radially from the Sun, and Earth revolves about the Sun; thus, the magnetosphere's elongated shape axis varies to be always aligned with the Sun. The scientific goal of Geosail should be very important; it could be considered an appropriate continuation of the Cluster mission. Geosail should last 3–5 years with a mass lower than 200 kg, thanks to the solar-sail propulsion. Nevertheless, after a study of phase-A, news about Geosail and its funding are not conclusive. For instance, at the time of this writing, the official website of this mission was last updated on September 1, 2008.

## Solar Polar Imager

Solar sails are especially effective at performing missions that otherwise require a large amount of propellant. A particularly propulsive-intense maneuver is required to change the orbital inclination of a spacecraft, whether it orbits Earth, another planet or the Sun. The orbit's inclination is simply a measure of the angle the orbit plane makes with respect to some reference plane, which usually is either Earth's equator or the ecliptic. (Note that the term **ecliptic** refers to the (mean) path of the Sun on the Earth's celestial sphere; also, it refers to the plane of such path, which is a great circle of this sphere. Often, but erroneously, the terms **earth orbit** and ecliptic are used interchangeably. See Glossary for more explanation.) Moving from the initial launch orbit to another "angle" in orbit is very difficult, and conventional propulsion systems are limited in performing this maneuver by the amount of fuel they can carry.

Taking advantage of a solar sail's virtually unlimited ability to provide thrust, scientists are eager to place a spacecraft into a highly inclined orbit around the Sun in order to study what happens near its poles. Current observations of the Sun are limited to spacecraft launched from Earth, which remain nearly in the ecliptic (because they are launched from Earth, which inhabits the ecliptic), limiting our views to those near the solar equator or its mid-latitude regions. The proposed mission to study the Sun's poles is called the Solar Polar Imager, and it can only be realistically implemented with a solar sail propulsion system. The Solar Polar Imager spacecraft would benefit from the quadrupled increase in solar propulsive thrust available from operating at 0.5 AU. While the proposed mission is just a concept at this time, studies show that current solar sail technology could be used to implement the mission with a square, three-axis stabilized sail no more than 150 m on a side.

### L-1 Diamond

Taking the Heliostorm concept a step further and increasing the number of sunward, solar-observing, solar sail–propelled spacecraft in orbit around the Sun would dramatically increase our understanding of the star. The L-1 Diamond mission is one proposal to achieve simultaneous, multi-angle solar observations providing all the advantages inherent in having multiple views of complex phenomena. L-1 Diamond is proposed to be a constellation of four spacecraft working together to gather information about the Sun and the solar environment.

Three of the spacecraft would fly in triangular formation around the Sun. The fourth spacecraft would be located above the ecliptic, looking downward. Again, this mission could be achieved with first generation solar sails.

## MID-TERM (2025–2040) SAILCRAFT MISSION OPTIONS

Moving forward a few decades, we can reasonably expect major improvements in sail technology. Various sail structures and unfurlment techniques will have been perfected. Sails will be thinner, stronger and more temperature resistant. A number of exciting mission opportunities could be implemented during this time frame. One of these is the possibility of formation flying with a comet and returning comet samples to Earth.

### Comet Rendezvous

All the major planets and most asteroids circle the Sun in or near the same plane that Earth does—called the ecliptic. The constellations of the Zodiac are arrayed along the ecliptic track on the celestial sphere. Comets, on the other hand, are all distant from the ecliptic. It is very difficult to visit a comet at an arbitrary point of its orbit, because of the very high energy required to shift orbital inclination to match that of the comet. But given months or years, a solar sail in the inner solar system can perform such an inclination-cranking maneuver without the expenditure of an onboard propellant.

It's true that the current, conventionally propelled probes have visited the vicinity of a few comets, but these were short-term flybys (or in some cases fly-throughs) in which the probe traveled past the comet at relative velocities of 50 km/s or more.

A sail-propelled probe could utilize solar radiation pressure to match orbits with a comet and cruise in formation with that celestial object for weeks or months. Samples of comet material could be gathered for later return to Earth.

### Particle Acceleration Solar Orbiter

The Particle Acceleration Solar Orbiter would allow close-up imaging (<0.2 AU) and spectroscopic analysis of high-energy solar flares to determine their composition, development and acceleration mechanisms. Seeing the life cycle of a flare event from close solar orbit will significantly advance our understanding of these events.

## Mars Sample Return

Returning a sample from Mars has long been a goal for scientists interested in learning more about the possible development of life beyond Earth. Unfortunately, the complexity and associated high cost with performing this mission seem to push it indefinitely into the future. One aspect of the problem is the fuel required for the return trip to Earth. Getting a spacecraft to Mars requires a large, dedicated launch vehicle. Any sample return mission would have to include also a rocket landed on the surface of Mars to return the sample from the surface back into space. Once back in space, the sample would then have to be transported to Earth. To do this chemically would require multiple rocket launches. We simply cannot launch at one time enough fuel to get our spacecraft into orbit for the Mars ascent rocket, and the propellant required for returning to Earth.

If the mass required for any leg of the trip can be significantly reduced, the cost of the mission would decrease, making it more likely to happen. Solar sails provide a lightweight option for returning the sample from Mars to Earth. The scenario might go something like this:

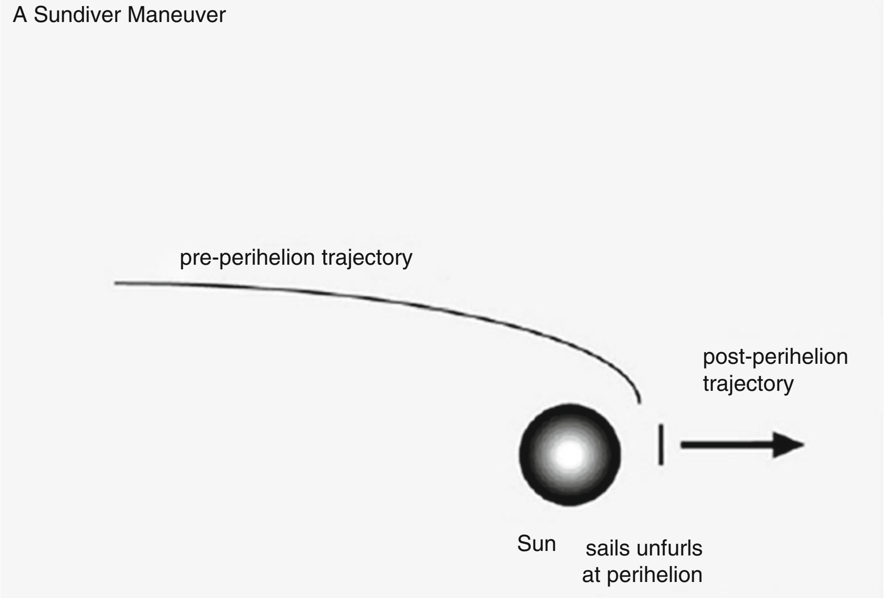
1. A rocket launches the mission spacecraft from Earth.
2. The spacecraft enters Martian orbit, sending a lander to the surface.
3. The lander collects the sample of interest and sends it back to space using a rocket that accompanied it to the surface.
4. The rocket has a rendezvous with a solar sail-propelled craft in Martian orbit, transferring the sample.
5. The sailcraft returns the sample to some parking orbit about Earth.
6. An orbital transfer vehicle moves the sample to the future space station. (Alternatively, the sailcraft could return the sample to the lunar base.)

In this scenario, the lightweight solar sailcraft replaces the heavy chemical propulsion stage that would otherwise be required to return the sample to Earth for analysis.

## Aerocapture Experiments

One method of reducing the cost of some scientific space missions is to utilize a new technique called **aerocapture**. In performing this maneuver, a space probe must be directed toward a solar system object with an atmosphere, such as the planets Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune, or Saturn's satellite Titan. Instead of using rockets to decelerate for capture from a Sun-centered to planet-centered orbit, the craft grazes the planet's atmosphere. If the orbit is precise, atmospheric friction will decelerate the spacecraft sufficiently for planetary capture.

A number of specialized devices—aeroshells and ballutes (which are a cross between balloons and parachutes)—could be deployed by a space probe performing an aerocapture maneuver. Preliminary studies reveal that certain solar sail configurations could be applied during aerocapture. An added bonus to sail application in aerocapture, of course, is that the sail can utilize solar radiation pressure to accelerate a spacecraft, as well as functioning like a parachute to slow one.



9.3 A sundiver maneuver

One possible sail-aerocapture probe would be a Titan orbiter. After Earth launch, the sail would be utilized to accelerate the spacecraft toward Saturn. Arriving at Saturn, the sail would be utilized as an aerocapture device to steer the craft into a Saturn-centered orbit with an apoapsis (high point) near Titan. The sailcraft would once again apply aerocapture, grazing Titan's atmosphere with a fully unfurled sail, to become a satellite of that tantalizing small world.

Another mission option would involve a sail launch toward Mars, sail-aided aerocapture into Mars orbit and sail-aided maneuvering in the Mars system. Samples could be returned from the surfaces of Mars's small satellites Deimos and Phobos. If these samples contain ample amounts of water and other volatile materials, later human-occupied ships visiting the Red Planet could utilize these satellites to top off their fuel tanks.

## Extrasolar Probes

One might suppose that a low thrust Sun-pushed gossamer spacecraft will have no application in ventures testing the fringes of galactic space. One would be wrong!

In a maneuver called "sundiving" by science fiction authors Greg Benford and David Brin, the sailcraft is initially placed in a parabolic or elliptical solar orbit with a perihelion (point of closest solar approach) as close to the Sun as possible (Fig. 9.3).

At perihelion, the sail is pointed toward the Sun and the craft is ejected from the solar system. Contemporary, Earth-launched sail technology seems capable of achieving solar system escape velocities as high as 50 km/s, with or without the giant planet gravity assists utilized to accelerate Pioneers 10 and 11 and Voyagers 1 and 2.

The solar system escape velocities possible utilizing the sundiver maneuver are far in excess of the velocities of the Pioneers and Voyagers. Within a flight time of about two decades, a sail-launched extrasolar probe could reach the heliopause—the boundary between solar and galactic influence—at 200 AU or so from the Sun and measure local field strengths and particle densities. If the probe can survive another few decades—not impossible in light of Pioneer's and Voyager's longevity—data could be returned from the inner focus of the Sun's gravitational lens at 550 AU, which would provide a check on Einstein's general relativity theory as a mission bonus.

The possibility to fly by the Sun and get a high escape speed from the solar system is much more than a science fiction idea. We have a strict mathematical theory,[2] which tells us that even without resorting to far future technologies, a sufficiently light sailcraft could be controlled in such a way as to reach the solar gravitational lens with a speed of 120 km/s, at least. Of course, emerging technologies could do excellent things for the designs of whole sailcraft and help us to transform such theoretical results into reality.

Some may conservatively argue that probes to the edges of interstellar space may have little relevance to terrestrial life. But since mass extinction events on Earth may be linked to galactic influences, a few such interstellar craft may well be launched as our sail technology improves. And these early flights will only be the start of the sail's flirtation with the galactic abyss. Because the solar sail is scalable, we may view these early efforts as humanity's first true starships.

## FAR-TERM (2040+) SAILCRAFT MISSION OPTIONS

As time elapses, humanity's technological progress is certain to continue. After 2040, a substantial in-space infrastructure may well exist. There may be facilities in near-Earth space where space resources or Earth-launched material can be processed to produce solar sails with near theoretical maximum performance.

Larger sails will be possible in this time frame—with dimensions measured in kilometers. And these large, space-manufactured sails will perform better than their Earth-launched predecessors.

### Human Exploration Sailships

Current technology, micron-thick, Earth-launched sails are not yet up to the support of human exploration of the solar system. These sails are too small to carry the tens of thousands of kilograms necessary to support humans between the planets and exploration gear. Also, sail-implemented missions to Mars (for example) using today's sail technology would be of longer duration than rocket-propelled interplanetary ventures.

But when sail linear dimensions are measured in kilometers and sail thicknesses are in the sub-micron range, all this will change. The sail may then become the most economical means of transport throughout the inner solar system. New constellations of twenty-first

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[2] This one is the theory of fast solar sailing, initiated by author Vulpetti in 1992, and completed by him in 2012. References to this theory can be found in Part V, a more technical part of this book.

century space clipper ships might be visible in Earth's night skies as they spiral outward toward Mars or the asteroids. The first of these might be rather modest, a mere 800 m on a side, carrying 5,000–10,000 kg payloads between Earth and Mars on a recurring basis. While too massive to launch from Earth, such a large diameter sail could be readily made in space to perform this mission without overly stressing the other sail figure of merit—areal density.

Initially, these craft will support exploration missions. But since sailships should be capable of many interplanetary roundtrips without fuel expenditure, human settlements will also benefit from the technology as they begin to grow on celestial bodies beyond the Moon.

We like to point out here that, via the management of sails of many squared kilometers, an efficient Earth-Mars-Earth (or Moon-Mars-Moon) reusable shuttle should become a reality. In the winter 2014, Prof. C. Circi (and his team) and author Vulpetti began a preliminary study of such a shuttle concept at Rome University La Sapienza's Department of Astronautical Engineering.

## Rearranging the Solar System

Although Mars exploration has captured the hearts and minds of the public, altering orbits of some near-Earth objects (NEOs) of asteroidal or cometary origin may be of much greater terrestrial significance.

There are thousands of these bodies scattered between the orbits of Venus and Mars. And it is known that they occasionally whack Earth, with disastrous consequences.

The most famous of these impacts occurred about 65 million years ago in the Yucatan region of Mexico. Eons before the Mayan rulers sported in the warm waters of the Caribbean, the tremendous fires and ash from the impact of this 10 km object may have helped cause the demise of the dinosaurs and the rise of mammals to ascendancy.

But smaller objects, such as the 100 m radius object that impacted in Tunguska Siberia in 1908 with the force of a 20 megaton hydrogen bomb, strike much more frequently than NEOs of the dinosaur killer's size—at intervals of a few centuries or less.

Although in principle there is a certain (low) risk of Earth-NEO collisions in the course of centuries, do not panic; unlike our ancestors, we can do something about this threat, taking responsibility for our own future.

Although nuclear explosives are certainly an option to divert a NEO targeting Earth, sails present a much more elegant option. A large, thin solar sail deployed at an NEO would increase both the reflectivity and the effective area of the NEO, allowing for a decades-duration alteration in the NEO's orbit, converting a direct hit on Earth into a near miss.

## Space Mining

If we are going to explore the NEOs, why not make use of them? Many materials are present in or on these small celestial bodies, including (at least in some NEOs) water.

One way to support an expanding space infrastructure and render it less dependent on Earth is to mine NEOs as we rearrange their orbits and ship the materials back to space processing facilities near Earth. Solar sails may provide an economical, though slow, method of altering the orbit of an NEO to allow its riches to be mined and exported back to Earth and elsewhere.

The NEO-obtained material may be used to create a geosynchronous ring of solar power satellites to beam energy back to Earth, rendering the West's current oil addiction obsolete.

Solar sail freighters, perhaps under robotic control, would make very effective transporters of material from the NEOs. Such an application may prove to be the most economically significant of all sail uses in this time frame.

### Oort Cloud Explorers

As a prelude to interstellar travel, space agencies after 2040 may develop an interest in probing the inner fringes of the Sun's Oort comet cloud.

Although some comets occasionally approach the Sun, where they display beautiful comae and tails, most reside in the frigid wasteland beyond the most distant planet of our solar system. Perhaps a hundred billion or a trillion of these ice balls are out there, some as close as a few thousand astronomical units, others as far out as 70,000 or 80,000 AU. Occasionally, a passing star or other celestial influence disrupts some of these objects from their stately orbits and shunts them sunward as a comet swarm.

We have probed some of the comets that regularly visit the inner solar system, but it would be nice (and informative) to visit these relics of solar system formation in their natural realm.

This is a task for the Oort cloud explorer, perhaps the ultimate sailcraft before a true starship. Imagine a sail 100 nm thick, perhaps a kilometer in radius, which is constructed of material capable of withstanding a perihelion pass of about 0.05 AU (about 10 solar radii). Such a craft could perform a Sun dive and project its payload toward the stars at velocities in excess of 500 km/s.

Although the Oort cloud explorer would take perhaps 2,000 years to traverse the 40 trillion km (4.3 light year) gulf between our Sun and its nearest stellar neighbor, it could certainly survey the Oort cloud out to a few thousand AU during its operational lifetime.

### The Ultimate Future: Sailships to the Stars!

Interstellar travel—flight to the stars—seems so easy in the typical Hollywood space epic. A ship silently drifts in interplanetary space, and a button is pushed. Marvelously, the local fabric of space-time is warped and distorted. The spacecraft takes an interdimensional shortcut across the universe, emerging instantly into normal space near a star many trillions of kilometers distant from our solar system!

If only it were so easy in the real world! Such interdimensional shortcuts are possible in theory, but not easily achieved in practice. To warp space effectively, we might need the mass of a star squeezed into the volume of a small terrestrial city—a so-called black hole. Yes, black holes may be shortcuts to distant realms of space and time, but tidal effects would doom a spacecraft foolish enough to approach one closely.

We might consider using angular momentum (spin) or magnetic fields to replace such a gravitational singularity, but how do you keep a structure from blowing apart if it must be spun at half the speed of light to produce an angular momentum-induced space warp? And to do it magnetically might require production of impossibly strong magnetic fields.

If only it were as easy to take an interdimensional shortcut as portrayed by Hollywood! Many physicists have calculated that contemporary physics actually forbids such techniques, which are based on the assumed existence of exotic matter having *negative* energy density (not to be confused with antimatter). In addition, even if we could produce a tunnel through space—a **wormhole**—there are stability issues. The energy of the known universe might be required to stabilize the thing long enough for a ship to pass through! Recently, some physicists computed a much lower amount of stabilization energy, but still incredibly high for what we can manage (once we arrive at knowing what exotic matter actually is via advanced measurements). An authoritative review of this topic can be found in Everett and Roman's *Time Travel and Warp Drives* [1].

But interstellar travel is still possible, even if space warps are quite unlikely. Real starships will be slower than celluloid craft, and travel times will be longer. Before considering applications of the solar sail to interstellar travel, let's briefly examine some of the other approaches that have been suggested.

## Relativistic Starflight

All right, so instantaneous interstellar travel seems to be beyond us. But what about flight at relativistic or near-optic velocities, close to 300,000 km/s? Even though travel at near light speed would take years or decades from the point of view of Earth-bound observers (even to near stars), special relativity predicts that such flights will be much shorter from the point of view of onboard crew members.

When I.S. Shlovskii and Carl Sagan published their classic, *Intelligent Life in the Universe*, in the 1960s, they noted that only two modes of relativistic travel seemed physically possible. These are the antimatter rocket and the hydrogen-fusing ramjet. Although their operation would not violate the laws of physics, there are serious technological and economic limitations to the near-term development of these travel modes.

Every elementary subatomic particle has a corresponding antiparticle (see Chap. 3). Put some matter and a corresponding mass of antimatter together and—boom! All the matter and antimatter is instantly (and explosively) converted into energy. The matter-to-energy conversion efficiency of the matter–antimatter reaction is more than 100 times greater than the best we can do with nuclear fusion and fission.

So all we have to do, conceptually, is load our interstellar rocket with lots of hydrogen and an equal mass of antihydrogen. If the matter and antimatter are allowed to slowly interact, the reaction can accelerate the craft to relativistic velocities.

But there are two big problems. First is the economics of antimatter production. Yes, we can produce tiny quantities (nanograms per year) of the stuff in our most energetic nuclear accelerators. But the cost is staggering. If the entire US economy were devoted to the production of the stuff, even allowing for economies of scale, it is doubtful that the country could produce even 1 g in a decade.

Even if a breakthrough alleviates the economic issue, there is another problem. How do we safely store the stuff for years or decades during the starship's acceleration process? Remember that if even 1 mg of antimatter comes in contact with the storage chamber (which is constructed of normal matter), the ship will instantly self-destruct!

In principle at least, the hydrogen-fusing ramjet is a more elegant solution. There are plenty of ionized hydrogen particles—protons—adrift in the interstellar medium. A properly configured electromagnetic field (a so-called "ramscoop") could conceivably be utilized to collect these over a thousand kilometer radius from the interstellar medium in front of a starship. These collected particles could then be directed into an advanced nuclear-fusion reactor and joined together (fused) to create helium and energy. The reaction energy could be applied to the helium exhaust to accelerate the starship up to relativistic velocities.

But as with the antimatter rocket, there are two major issues to constructing a ramjet. In this case, both are technological. First and foremost is the low reactivity of the proton–proton reaction. While it is true that almost all stars, including our Sun, radiate energy produced by proton fusion, this reaction is many orders of magnitude more difficult to achieve in the laboratory than thermonuclear fusion reactions used in the hydrogen bomb and our experimental fusion reactors. Barring a major breakthrough, we may never be able to tame proton fusion without carrying around a stellar mass—a somewhat inelegant approach to interstellar travel.

Even though other reactions could be used to propel slower ramjet derivatives, there is a secondary technological issue. Most electromagnetic ramscoop designs are much better at reflecting interstellar protons than collecting them. It is far easier to design an electromagnetic drag sail to slow a speeding starship than a ramscoop to collect fuel from the interstellar medium.

So we will abandon relativistic starflight concepts from our consideration. What a pity—but we still could have "slow boats" that would take centuries to cross the gulf between our solar system and its nearest stellar neighbors.

## The Nuclear Option

The first feasible method of interstellar travel to emerge is a daughter of the Cold War. First as a space interceptor and then as a backup to the Saturn V Moon rocket, the US Department of Defense and NASA considered Project Orion, a spacecraft propelled through space by the thrust of exploding nuclear devices. Tested with conventional explosives (since atmospheric nuclear detonations are prohibited by international treaty), a subscale Orion prototype was successfully flown during the 1960s and is on permanent display in the Smithsonian Air and Space Museum in Washington, DC.

With the technique of nuclear-pulse propulsion demonstrated, physicist Freeman Dyson moved the concept to its theoretical and economic limits in an epochal paper published in 1968 in *Physics Today* [2]. If the Cold War thermonuclear arsenals of the US and the Soviet Union had been devoted to the propulsion of huge Orions constructed in space, small human populations could be transferred to neighboring stellar systems. Travel times to the Sun's nearest stellar neighbors—the Alpha/Proxima Centauri system—would be in the range 130–1,300 years.

Of course, no nuclear power can realistically be expected to unilaterally donate its arsenal to the cause of human advancement. So the British Interplanetary Society commenced Project Daedalus in the early 1970s to evaluate the possibility of a sanitized version of nuclear-pulse interstellar propulsion.

The Daedalus motor would employ the concept of inertial fusion, a technique that is currently approaching laboratory realization.[3] Small pellets of fusible isotopes, preferably deuterium and helium-3, would be ejected into the craft's combustion chamber at the focus of laser or electron beams. These beams would compress the pellets and raise their temperature to the point at which thermonuclear fusion can occur. One-way interstellar travel time for small human communities would be measured in centuries, and robot probes would be faster.

But there was one catch. Helium-3, although abundant in the Sun, is extremely rare on Earth. To implement Daedalus, we would have to develop a space infrastructure capable of locating and mining this isotope from resources such as giant planet atmospheres, the solar wind, or possibly the lunar regolith.

If we wish to conduct early interstellar ventures, Daedalus is not practical. But, surprisingly, the solar sail provides an alternative propulsion possibility.

## Solar Sail Starships

You might think at first that the solar sail is useless in the dark void of interstellar space. After all, today's sails are flimsy affairs capable of small accelerations—typically one ten thousandth of Earth's surface gravity (0.0001 g).

But recall this—solar flux is an inverse-square phenomenon, meaning that as we halve the distance between the sail and the Sun, the sail's acceleration increases by a factor of four. If we can unfurl our sail very close to the Sun, then accelerations of 1 g or higher are possible (but only there).

Before 1980, two American research teams were independently evaluating the feasibility of solar sail starships. Some of the research was performed as part of a NASA Jet Propulsion Laboratory (JPL) study: the TAU (thousand astronomical units) probe. This was an interstellar precursor probe, departing the solar system at 50–100 km/s. Too slow to reach the nearest stars in less than about 13,000 years, TAU would sample particles and fields in the nearby interstellar medium and perform astronomical observations.

Although the favored propulsion system for TAU was the nuclear-electric drive in which a fission reactor's energy is used to ionize and accelerate argon atoms, a solar sail unfurled near the Sun was considered as a backup mode of propulsion. Unfortunately, the senior analyst on this aspect of the study, Chauncey Uphoff, was permitted to publish his star sail extrasolar probe results only as an internal NASA memo.

At about the same time, author Gregory Matloff, in collaboration with Michael Mautner and Eugene Mallove, was independently evaluating solar sail starship propulsion as an alternative to nuclear pulse. Most of this work was published during the 1980s as a series of papers in the *Journal of the British Interplanetary Society (JBIS)* [3–5].

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[3] Although at considerable expenditure and with the requirement of substantial technological advance.

An optimized interstellar solar sail probably would be constructed in space using a nanometers-thin monolayer of a highly reflective, temperature-tolerant material—possibly a metal such as beryllium, aluminum or niobium. The sail would be affixed to the payload, utilizing cables with the tensile strength of diamond or silicon carbide.

In operation, a partially unfurled sail might be mounted behind a chunk of asteroid that has been machined to serve as a sunshade. The sail and occulting sunshade would then be injected into a parabolic solar orbit with a perihelion solar distance measured in millions of kilometers.

Approaching perihelion, the partially unfurled sail would emerge from behind its sunshade and be rapidly blown from the solar system. As the solar distance increases, the sail could be gradually unfurled and ballast released to control acceleration.

Analysis revealed that acceleration times measured in hours or days were possible. By the time the ship reaches the orbit of Jupiter, the sail could be furled, since acceleration has fallen to a negligible value. The sail could be used as cosmic ray shielding and later unfurled for deceleration. Flight times to Alpha Centauri, even for massive payloads that could carry human crews, could approximate a millennium. Of course the hyper thin sail sheets required to "tow" such large, multimillion kilogram payloads, would be enormous—in the vicinity of 100 km.

One way to increase performance of a sail-equipped starship is to "park" a solar-pumped laser or microwave power station within the inner solar system and use this device to beam collimated energy to a sail-equipped starship very far from the Sun. This approach is considered in more detail in the next chapter.

## FURTHER READING

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