6

Principles of Space Sailing

The romantic-sounding term **solar sail** evokes an image of a majestic vessel (similar to the great sailing ships of the eighteenth century) cruising the depths of interplanetary space (Fig. 6.1). In a very literal sense, this imagery is very close to the anticipated reality of solar sails. Very large and diaphanous sail-propelled ships will traverse our solar system and perhaps, one day in the future, voyage to another star. From what will these ships be made and how will they work?

The **solar wind** is a stream of charged particles (mostly hydrogen and helium) emitted by the Sun. The solar sails, which are the primary focus of this book, are not blown by the solar wind, though there have been proposed "sails" that will do just that. The "wind" that blows a solar sail is sunlight. The ever-present, gentle push of sunlight will eventually accelerate our starships to speeds far above that achievable by chemical or electric rockets—or the solar wind.

WHAT IS A SOLAR SAIL?

To understand how sunlight propels a solar sail, one must first understand at least a little bit about the interaction of light with matter. When sunlight, which has momentum, falls on an absorptive surface (consider a surface painted black), very little sunlight reflects from the surface; most is absorbed. In space, where there is no air resistance and an object is essentially free from other forces, the sunlight falling on a black sail will transfer its momentum to the sail, causing the sail to move. If the same material is now painted with a light-reflecting material (like a mirror), it will reflect the photon instead of absorbing it. Like the black sail, this one will also begin to move, and the reflective sail will accelerate at a higher rate than the one with a dark surface. The reflected light transmits more of its momentum to the sail than the light that was absorbed. The principle of momentum transfer applies to all forms of sails, including photon sails, magnetic sails, plasma sails and, very recently, electric sails.

G. Vulpetti et al., *Solar Sails*, Springer Praxis Books,
DOI 10.1007/978-1-4939-0941-4_6

6.1 Solar sails will propel our starships in much the same way that wind gave the great sailing ships their energy for more earthly exploration (Courtesy of NASA)

MOMENTUM TRANSFER

You can test this at home using a rubber ball, a ball made of modeling clay (or Play Doh) and a hinged door. First, throw the ball of modeling clay at an open door and notice how far the door moves. The clay will most likely stick to the door, mimicking the absorption of light on a dark-colored sail. Next, open the door back to its initial position and throw the rubber ball, trying to throw with the same force as was used with the clay, and notice how far the door moves. If the experiment goes as it should (which is not always the case in experimental physics!), the rubber ball will bounce off the door and cause it to close farther than was achieved with the ball made of clay. In this case, the rubber ball (like the light) is reflected from the door, transferring twice as much momentum to the door as the ball of clay. This is analogous to the light reflecting from the sail.

At first thought, it might appear that a solar sail would be very limited in the directions it can move. For example, it seems intuitive that a solar sail might be used for a voyage to Mars or Jupiter, but not to Venus or Mercury. Venus and Mercury are sunward of Earth and one might think that the Sun will therefore constantly push a sail away from them. If the planets were not in orbit about the Sun, this would be correct. But the planets *are* in orbit about the Sun and we can take advantage of this fact to allow a solar sail to fly either toward or away from it.

Just like a wind-powered sailing ship, a solar sail can tack—sort of. Instead of maneuvering back and forth "into" a head wind so as to move the ship toward the prevailing wind (sunlight), the sail can be tilted to alter the angle at which the light strikes and reflects from the sail—causing it to either accelerate or decelerate. Earth orbits the Sun at 30 km/s (>66,000 miles/h), and any sail launched into space from Earth will therefore be in an orbit around the Sun with about the same orbital velocity. Since the distance a planet or spacecraft orbits around the Sun is determined by how fast it is moving, one may change that distance by either speeding up or slowing down. For a solar sail, this means changing the orientation of the sail so that it reflects light at an angle such that the momentum from the sunlight pushes the sail either in the direction it is already moving (acceleration) or in the opposite direction (deceleration). In either case, part of the light's momentum will be perpendicular to the direction of motion, causing the sailcraft to move slightly outward at the same time it is accelerating or decelerating. Adding up the various forces can be complicated, and making sure the net force is causing motion in the desired direction is an engineering challenge. Fortunately, we know how to model these effects and control them, just like a seasoned captain knows how to tack his boat against the prevailing wind.

Steamships and modern diesel electric cruise ships must refuel or they will be dead in the water. As long as the wind blows, a sailboat will be able to move. Like steamships, rockets must refuel. Solar sailcraft needn't bother! As long as the Sun shines, they will be able to use the sunlight to move. Unfortunately, this means they can only accelerate or decelerate in the inner solar system where sunlight is plentiful. When they reach distant Jupiter, the available sunlight is only a fraction of that available on Earth and the resulting forces on the sail are too weak. As we will discuss in later chapters, there are tricks that may be used to allow a solar sail to traverse the entire solar system (or stay in it on recently discovered orbits) and perhaps take us to the stars.

In order to work, a solar sail must be of very low mass. The momentum transferred from sunlight to the sail is very small. If the sail and its payload are massive, the resulting acceleration will be slight. Simply stated, heavy is bad. What is needed are highly reflective, strong and lightweight sails. Modern materials science has provided several promising candidates and building viable sails from them is now within our reach.

HOW CAN THE SOLAR WIND BE USED FOR SAILING?

As mentioned above, there are other sail concepts that use entirely different physical processes to sail through space. Since three of them use the solar wind, it will be useful to discuss shortly the nature of that "wind" before describing how they harness it to produce thrust.

The solar wind is an ensemble of electrons and positively charged ions (mostly hydrogen and helium) produced by the Sun. Just like sunlight, there is a continuous stream of this plasma flowing outward from the Sun into the solar system. Unlike sunlight, there may be intense bursts of these charged particles emitted by the Sun at any time and in any direction. These ions and electrons race outward from the Sun at speeds in excess of 400 km/s. In fact, during periods of high sunspot activity, these speeds have been measured to be greater than 800 km/s! Could we use this wind to propel our spaceships?

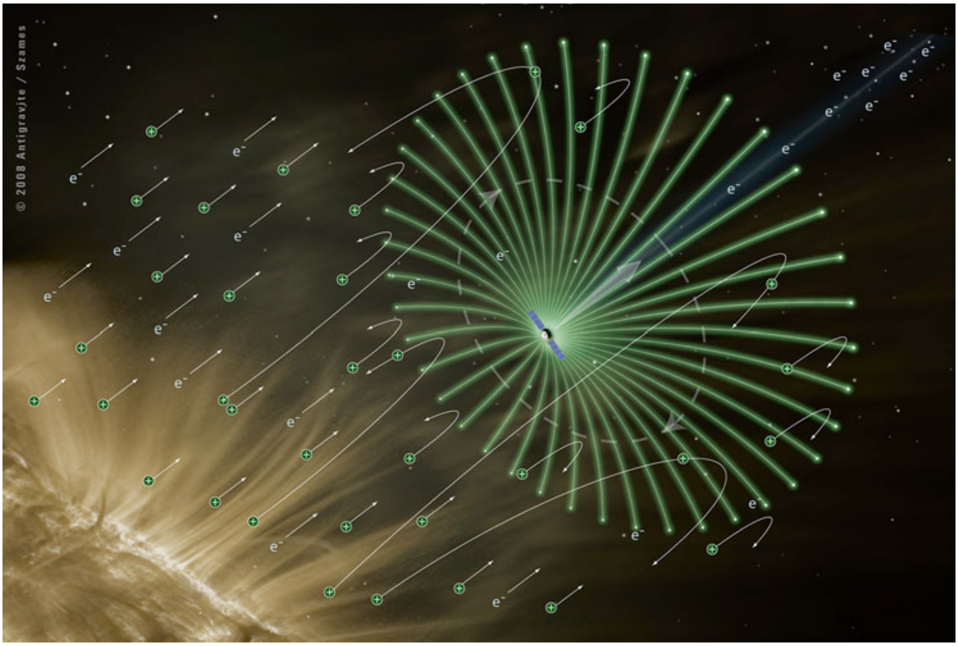
One way to take advantage of the solar wind for propulsion is the magsail. As the name implies, a magsail uses the interaction of the solar wind with a magnetic field to produce thrust. A charged particle moving through or into a magnetic field will experience a force, causing it to speed up, slow down or change direction, depending on the direction in which it is moving with respect to the field. And since Newton taught us that "for every action there is an equal and opposite reaction," the magnetic field will likewise be affected. In this case, the structure from which the field originates will experience the opposing force, giving it acceleration.

Conventional magnets made of iron are heavy (after all, they are made of iron!). Flowing a current through a wire can make lighter weight magnets. Flowing a large current in a low-resistance wire will produce a strong magnetic field. Magsail designers postulate the use of large superconducting wire loops carrying high currents to interact with the solar wind—sailing the solar wind.

While technically interesting and somewhat elegant, magsails have significant disadvantages when compared to solar sails. First of all, we don't (yet) have the materials required to build them. Second, the solar wind is neither constant nor uniform. Combining the spurious nature of the solar wind flux with the fact that controlled reflection of solar wind ions is a technique we have not yet mastered. The notion of sailing in this manner becomes akin to tossing a message in a bottle into the surf at high tide, hoping the currents will carry the bottle to where you want it to go.

In 2004, a new concept arose for trying to utilize the momentum flux of solar wind: the electric sail (see Further Reading below). Pekka Jahnunen, a researcher in the Finnish Meteorological Institute, is the originator of such concept. Like the magsail, this concept uses the solar wind for producing thrust. However, differently from the magsail, this sail interacts with the solar plasma via a mesh of long and thin tethers kept at high positive voltage by means of an onboard electron gun. In its baseline configuration, the spacecraft spins and the tethers are tensioned by centrifugal acceleration. It should be possible to control each wire voltage singly, at least to within certain limits. Thrust originates since the solar wind protons (remember that any proton in the Universe is positively charged) are repelled by the positive voltage of the mesh. In contrast, the electrons are first captured and then ejected away by an onboard electron emitter because accumulation of electrons would neutralize the mesh voltage rapidly. (The reverse configuration, i.e., electrons repelled and protons re-emitted, would produce a thrust about 2,000 times lower). Figure 6.2 is an artist picture of the electric sail concept. At this point one might object that the solar wind fluctuations are always present and no trajectory design would be reliable, quite analogously to the magnetic sails. However, this spacecraft could directly control the electric field that fills the space around it. In particular, the magnitude of the thrust could be controlled between zero and some maximum value by adjusting the electron gun current or voltage. Are such advantages sufficient, for instance, to issue a thrust level almost independent of the high variable solar wind intensity? Would it possible to use the electric sail for planetary defense? Would it be possible a rendezvous with outer planets? An active research is in progress.

It is important to realize that any propulsion type needs to be controlled for designing the vehicle's motion with high probability (the mathematical certainty is not achievable in practice). Otherwise, one could not know where it is going to or when it arrives at the target. Solar sailing cannot be an exception. Even sunlight is variable with time and mostly unpredictable. However, the fluctuation level is very low and we can design/predict a



6.2 Artist picture of the electric-sail concept. Differently from the magnetic-sail mode, current and voltage of the onboard field generator could be controlled (Courtesy of Alexandre Szames, Antigravité, Paris, and Dr. Pekka Janhunen, Finnish Meteorological Institute)

mission in all phases. Perhaps, this is the biggest difference between sunlight based and solar wind based sailcraft. There are in fact other phenomena in the solar wind that could increase the difficulty of propulsive application. However, such intriguing aspects—found out in the Space era—are considerably technical and therefore beyond the aims of this introductory chapter. Nevertheless, additional information about the solar wind can be found in other chapters of this book. In any case, the electric sailing concept deserves an investigation deeper than what done hitherto in literature.

Solar sails, magsails and electric sails are all examples of the creativity of the human mind unleashed. Using the immense energy of the Sun for propulsion is an idea whose time has come, and solar sails are poised to be the first to make use of this never-ending supply of fuel for space exploration.

FURTHER READING

For readers interested in science fiction stories that use the solar sail as a primary means of propulsion, we recommend Arthur C. Clarke, *Project Solar Sail,* ROC/Penguin, New York, 1990. A more technical treatment of solar sails can be found in Louis Friedman, *Starsailing, Solar Sails and Interstellar Travel,* Wiley, New York, 1988.

For graduate students in astronautical engineering or physics, a closer presentation of sailcraft concept and the solar-wind properties can be found at http://www.giovannivulpetti.it/SolarSailing/SailPhotonPhysics/tabid/64/Default.aspx, Lecture 2: Sailcraft Concepts, by author Vulpetti.

For technical readers interested in the electric-sail concept, we suggest the following scientific papers:

1. Janhunen P., *Electric sail for spacecraft propulsion*, J. Prop. Power, 20, 763-764, 2004
2. Janhunen, P., *The electric sail - a new propulsion method which may enable fast missions to the outer solar system*, J. British Interpl. Soc., 61, 8, 322-325, 2008
3. Janhunen, P., *On the feasibility of a negative polarity electric sail*, Ann. Geophys., 27, 1439-1447, 2009
4. Janhunen, P., *Increased electric sail thrust through removal of trapped shielding electrons by orbit chaotisation due to spacecraft body*, Ann. Geophys., 27, 3089-3100, 2009
5. Merikallio, S. and P. Janhunen, *Moving an asteroid with electric solar wind sail*, Astrophys. Space Sci. Trans., 6, 41-48, 2010
6. Janhunen, P., *Photonic spin control for solar wind electric sail*, Acta Astronautica, 83, 85-90, 2013