

Disruptive Technology

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In their 1995 article, “Disruptive Technologies: Catching the Wave,” Harvard Business School professors Joseph Bower and Clayton Christensen define two categories of new technology: sustaining and disruptive. Sustaining technology relies on incremental improvements to an already established technology. A good example is the conventional petrol engine used in automobiles; the principle on which it works has not changed in over a hundred years, but a modern car engine is much more reliable and efficient than that of a 1908 model-T Ford. Disruptive technology, on the other hand, is a revolutionary technology that suddenly, and often unexpectedly, displaces an established technology. Take, for instance, the rapid market takeover by digital cameras at the expense of long-proven and firmly established film-photography technology. According to Bower and Christensen, disruptive technology initially often lacks refinement, appeals to a limited number of people, and may not yet have a proven practical application (the idea is further developed in Christensen’s 1997 best-selling book, *The Innovator’s Dilemma*).

Tether technology has the potential to be a disruptive technology; if it works as advertised, it could radically change spaceflight and make conventional rocket propulsion systems largely obsolete. If so, it would not be the first time in history that an experimental technology totally replaced older, much better established means of transportation.

New Machines

After thousands of years of development, by the 19th century sailing ships had reached an incredible level of sophistication. They were fast, their rigging could cope with a variety of wind conditions, and their crews were trained to run the ships as best as possible. Then came the steam engine. At first, ships powered by steam could not really compete with sailing, because the machines were tricky to run, the paddles initially used to propel the

vessels were inefficient, and there was no worldwide infrastructure of fuel depots to enable an adequate range. Many were skeptical of the need for this new technology and doubted that the potential advantages would outweigh the investments. Was it really worth the trouble of completely converting the established and trusted system of sailing ship transportation? However, as the technology matured, steam boats quickly made the old sailing vessels obsolete. They became faster, were independent of the wind, and required much smaller crews, thus enabling rapid and predictable transportation at lower costs.

Later, in the early 20th century, cars were initially also greeted with skepticism. The first automobiles were expensive, broke down frequently, and could not travel on rough roads like horses could. Nor were they able to carry the huge amounts of cargo transported at high speed by steam trains. Nevertheless, eventually the car made it possible to transport people and goods in quantities and at an efficiency that would be impossible to reach with horses. Just think of how much food and stable space would be needed if everybody still used horses instead of cars, and how much slower local transportation would be. In addition, cars, unlike trains, are not limited to rails and can thus get to any village. They can be used by the driver and a few passengers, or even no passengers, while railroads are economical only if transporting large numbers of people or large amounts of cargo. The modern, large-scale economies needed to support the billions of people now inhabiting our planet could never be supported by horsepower alone or by trains alone.

The steamship and the car are just two examples of new technologies that dramatically disrupted the status quo, even when at the time their use did not seem to be required and their benefits seemed insufficient to warrant further investments. Space transportation now appears to be ready for a revolution as well. Even though conventional rocket propulsion can support all we do in space and has only relatively recently reached its maturity and become trusted, the limits of its performance capabilities and economic possibilities are already in sight.

Rocket Propulsion Limits and Limitations

Current space missions are heavily dependent on chemical rocket propulsion for the launch into space, for changing orbits, and for attitude control.

For the launch, rockets with chemical propulsion engines are used because there is simply no other way to put anything in orbit. Launcher

technology has improved a great deal over the last 60 years, so that rockets can now transport their payload more precisely to the desired orbit, are able to place multiple satellites into different orbits, and to do this with increased reliability and safety.

However, improvements in actual payload capability and launch cost have not been dramatic. Rocket engines have become somewhat more efficient, but the increases in thrust per amount of propellant have been relatively small. It appears we are currently reaching the limits of chemical rocket propulsion performance; any small increase in efficiency now requires such large amounts of development work, time, and money that it is often not worth the effort. In addition, the structural masses (the mass of the propellant tanks and support structures) of rocket stages have not improved much over the last 50 years. The launchers in use today are very similar to those that were developed in the 1950s to throw nuclear bombs at other countries. Modern rockets such as the American Atlas V and the Russian Soyuz are even direct descendants of early intercontinental ballistic missiles (Fig. 2.1).

All in all, the total mass that a certain type and size of launcher can put into a certain orbit has not improved very much since the 1960s. Looking, for example, at the total satellite payload mass that launchers can put into a low Earth orbit (LEO) as a percentage of their total lift-off mass, it becomes clear that this number has been close to 3.5 percent for the last 40 years or so (LEO extends to an altitude of about 2000 kilometers, or 1.240 miles). For geosynchronous transfer orbit (GTO) payloads, that percentage has been a steady 1.5 percent for the same period. A GTO is an elliptical orbit in which a geosynchronous orbit [GEO] satellite is initially launched in order to reach GEO altitude; at the GTO's apogee, a rocket motor is ignited to place it in a circular, geosynchronous orbit. For many modern launchers these percentages are even lower, depending on what the rocket is designed to do and how sophisticated it is (Figs. 2.2 and 2.3).

All launchers except the Space Shuttle are still of the expendable type, meaning they can be used only once. They drop off their empty stages along the way as a means of getting rid of dead weight. These stages then splash into the ocean or burn up in the atmosphere; outfitting them with retrieval equipment such as parachutes or deployable wings would make the launcher too heavy. Once the satellite cargo has been put in orbit, no part of these expensive machines is left for reuse.

Thus, this is an extremely expensive way to transport things. A medium-sized launcher such as the Russian Soyuz-Fregat can put a 1100-kilogram (2400-pound) spacecraft on a journey to Mars, but in doing so it throws away 26 metric tons (57,000 pounds) of precious rocket hardware (as well as



Figure 2.1: A Soyuz launcher, a direct derivative of the rocket used to launch the first satellite, Sputnik, and the first cosmonaut, Yuri Gagarin, is still being used to launch people and satellites. (Courtesy of the European Space Agency [ESA].)

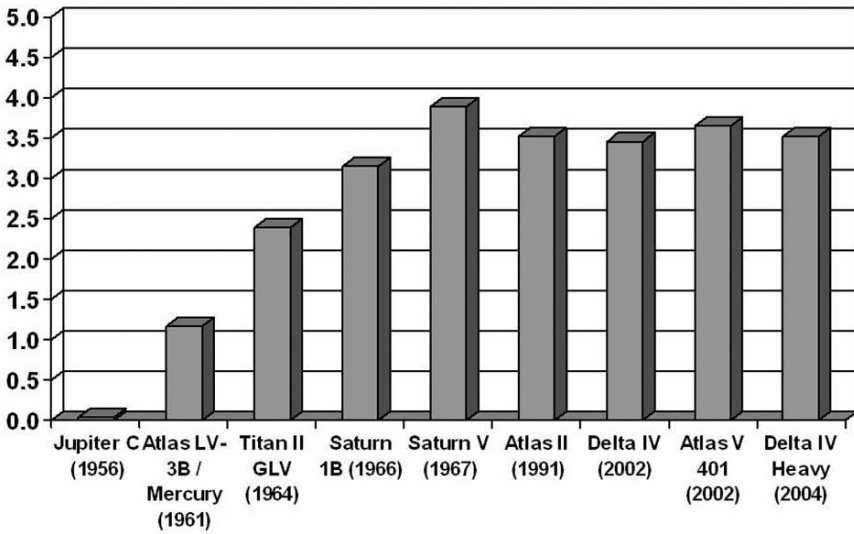


Figure 2.2: Payload mass as a percentage of a rocket's total lift-off mass, to an optimum low earth orbit (LEO), which is different for each launcher and launch site. The launchers shown represent the best of their generation in terms of payload mass to LEO.

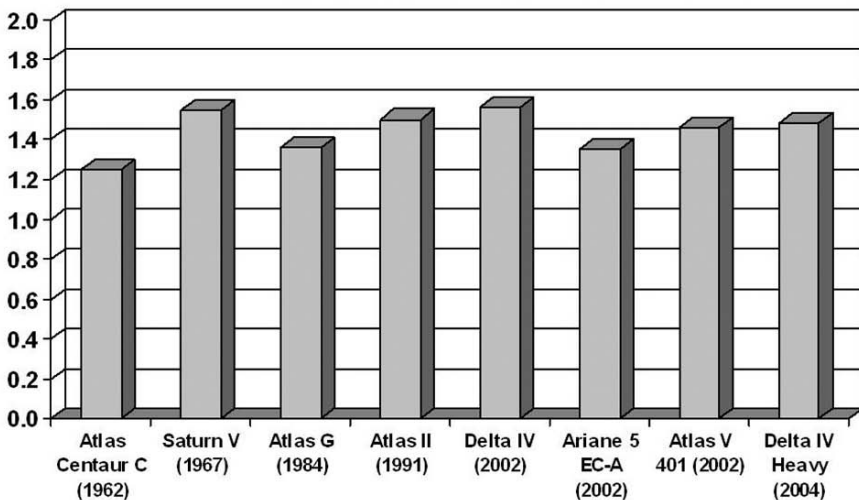


Figure 2.3: Payload mass as a percentage of a rocket's total lift-off mass, to a geostationary transfer orbit (GTO). The launchers shown represent the best of their generation in terms of payload mass to GTO.

289 metric tons (640,000 pounds) of propellant, but that is relatively inexpensive). A Soyuz-Fregat launch therefore costs on the order of \$45 million, which is actually relatively cheap compared to most European and United States rockets. Improvements in how we develop, produce, and operate launchers can still decrease launch costs somewhat, as shown by SpaceX with its Falcon series of launchers, but we should not expect dramatically lower launch costs per kilogram satellite in orbit with any new expendable launchers.

An obvious way to lower launch costs is to reuse rockets. Instead of having to pay for a completely new one every time we need to put up a spacecraft, we would then only need to pay for the propellants, operations, and maintenance of the launch vehicle, such as with an airplane. Planes are not thrown away after each flight.

The reason that expendable rockets are still the norm is that we have not had much success developing reusable systems. To make a launch vehicle capable of being used again, it needs additional equipment to return to Earth. Heat shields, wings, parachutes, and additional propellant for landing make reusable systems relatively heavy. As the satellites on top of expendable launchers comprise only a few percent of the total launch mass, the mass available for useful payload is easily eaten up by additional components added to make the system reusable. The fact that rocket engine efficiency and structural mass reductions are already close to their achievable limits means that it is very hard to compensate the mass growth in a reusable launcher design. Many concepts for reusable systems, therefore, would be capable only of launching and flying back the bare vehicle itself, without any mass allocation to spare for spacecraft cargo such as satellites and space station modules.

Reusable launchers are also more difficult and therefore more expensive to develop than expendable launchers. On top of the difficulty of developing something that can go into orbit, now the vehicle also needs to be designed to come back, which involves reentry into the atmosphere, a descent phase, and a soft landing. Furthermore, the use of such launchers requires not only a launch pad but also the development of additional infrastructure, such as a safe landing area, vehicle and engine maintenance buildings, and logistics facilities to store and manage the distribution of spare parts.

Instead of these recurring costs for a reusable system, every expendable launch involves a brand new vehicle, and therefore operations are limited to the launch preparations and the actual flight. In addition to this, however, a reusable launcher requires inspection and maintenance before each subsequent mission. The operations costs for reusable systems are therefore also higher than in the case of expendable rockets. The Space Shuttle orbiter,

for example, excluding the effort for its main rocket engines, requires a maintenance team of some 90 people, each working about 1000 hours after each mission. This costs about \$8 million per flight on maintenance labor alone. Together with the maintenance hours on the three large Space Shuttle main engines and the two reused solid rocket boosters, this represents a huge amount of money that does not need to be spent when using expendable, single-use rockets. Moreover, the Space Shuttle system is not fully reusable: the large brown external tank is discarded during each flight, so a new one is needed for every mission.

The higher development, infrastructure, and maintenance costs mean that operating reusable launchers can result in lower launch prices only if they make many flights each year. It is just like with commercial airlines, which need to keep their planes in the air for as many hours as possible to keep costs down. This requires short maintenance cycles; otherwise a large and therefore expensive fleet of vehicles would be needed. To justify launching many spaceflights, we also need a large number of customers who require the launch of many more payloads than is currently the case. The launch market will significantly increase in size only if launch prices drop dramatically, which in turn requires efficient reusable systems with little maintenance needs. This is a really difficult catch-22 situation: launches could become cheaper if there was a sufficiently large market, but this market will not grow until launch costs drop significantly.

The maintenance of the (partially) reusable Space Shuttle turned out to be so time-consuming that the initial expectations of launching some 60 missions per year never became a reality; in a good year, the shuttle is launched about six times. The high maintenance and replacement costs and the low launch rate have resulted in very high launch costs. Before the Columbia disaster, a Space Shuttle launch with all its complicated pre-launch activities and human spaceflight equipment was costing on the order of \$300 million to \$500 million per flight. The additional safety constraints put in place after the loss of Columbia probably put the current cost way over half a billion dollars per flight. This makes the Space Shuttle the most expensive launch vehicle, both in total launch price and in cost per kilogram payload put in orbit. For the current relatively few satellite launches per year, it is cheaper to use expendable, one-shot rockets. The reason that the Space Shuttle is still in use despite its disadvantages is that it is the only vehicle the United States has available for human spaceflight.

In fact, for the relatively few crewed missions it foresees to the Space Station in the 2010s and to the Moon in the 2020s, NASA has found that it will be less expensive to operate classic expendable rockets and capsules rather than some kind of reusable shuttle system. NASA has therefore

decided that the successor of the Space Shuttle to launch astronauts, the Ares I launcher, will be an expendable system that is not too different from the rockets used to launch the early pioneering astronauts of the Mercury, Gemini, and Apollo space programs in the 1960s. Ares I will be topped with an Orion capsule that may be partly reusable, but is otherwise very similar in design to the Apollo Command and Service Module combination of 40 years ago (Fig. 2.4). For launching large cargoes such as lunar base modules, NASA will develop the Ares V, which will be a mostly expendable rocket (only the solid rocket boosters derived from the Space Shuttle system may be reused) (Fig. 2.5). New versions of the Ariane, Atlas, Delta, and Soyuz rockets are also still being developed, and it does not look like these expendables will become obsolete and replaced by reusable launch vehicles anytime soon.

Radically lowering launch prices for traditional rocket propulsion systems, even by means of reusable equipment, is extremely difficult. The SpaceX company in the United States is now offering its expendable Falcon 1 launcher, and the advertised launch price of \$7 million means a significant drop in price with respect to that of the competition, which is about double for the same payload. Using larger successors of Falcon 1, SpaceX believes it will be able to offer prices on the order of \$1000 per kilogram payload in low Earth orbit by 2010. Since the current cost is about \$5000 per kilogram for large launchers (and about \$10,000 per kilogram for small launchers with small payload capabilities), this would mean a significantly lower launch cost. However, it is still a lot of money. For example, taking into account also the mass of the spacecraft, flying as a space tourist with SpaceX would still mean a ticket price of about \$1 million to \$1.5 million—much less than the \$20 million paid by recent space tourists flying with the Russian Soyuz to the International Space Station, but still a lot more than most people can afford.

Some private companies are developing reusable launch vehicles, having determined (or hoping) that with currently available technology it may yet be possible to develop cost-efficient reusable launch vehicles. Government space agencies such as the European Space Agency (ESA) and NASA have not completely given up on reusable launchers either. Smart concepts such as the suborbital hopper may still make lower launch costs possible. A hopper is a reusable vehicle that does not accelerate all the way up to orbital velocity but delivers payloads in space at almost orbital speeds. Such a launcher saves huge amounts of propellant by not having to boost its own mass into orbit; the mass of an additional booster stage required to give the cargo the bit of extra speed it needs is very limited in comparison. Also, future technology such as rocket and jet engine combinations able to make use of the oxygen in the atmosphere for important parts of the flight, and thus requiring less onboard propellant, may enable the development of

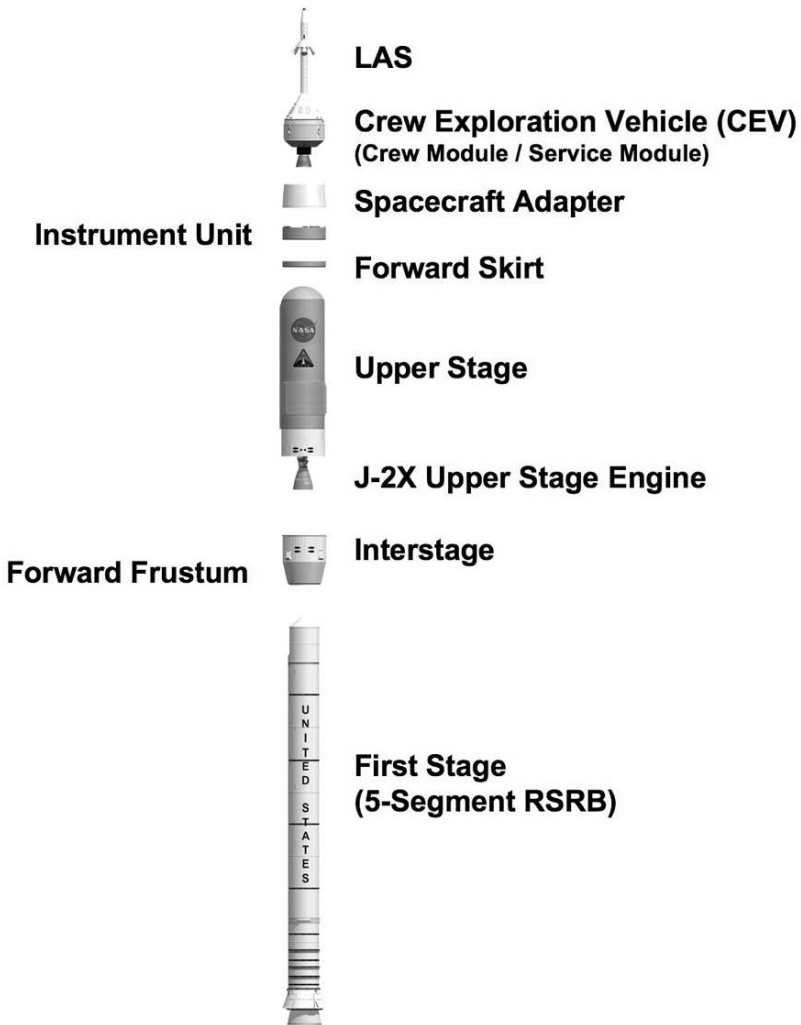


Figure 2.4: The Ares I launcher will consist of an extended Space Shuttle solid rocket booster and a new upper stage, and will not be reusable. (Courtesy of NASA.)

efficient space planes. If novel concepts and technology can drop launch prices to levels that make it affordable for smaller countries and organizations to launch satellites and people into space, the market may grow enough and launch rates may increase sufficiently to warrant the development of even better reusable systems.

However, a completely different new technology may be needed to radically lower the costs of access to space. Even if new and reliable launch systems reduce these costs by a factor of ten, it may take more than that to

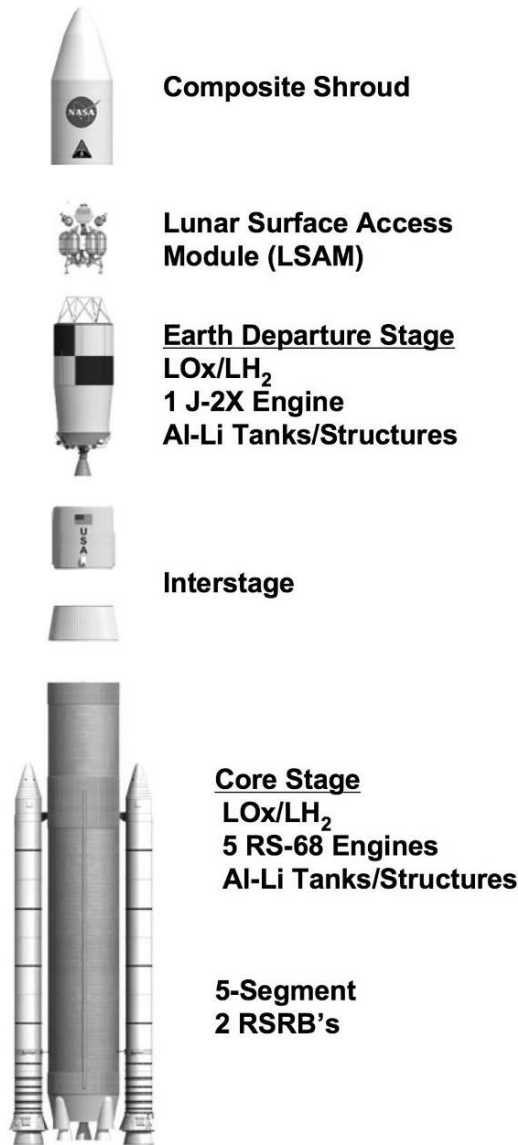


Figure 2.5: The Ares V will be a heavy lift, nonreusable launcher for large payloads. (Courtesy of NASA.)

make new applications such as lunar mining, microgravity industries, mass space tourism, and Mars colonization economically viable. Instead of \$1000 per kilogram payload in low Earth orbit, it would take prices on the order of \$10 per kilogram or less to make the cost of a flight into space comparable to that of transportation by airplane.

Rocket propulsion is not only used to launch things, it is also the main means for maneuvering and changing orbits, and for controlling the attitude of spacecraft. Relatively large thrusters are used for trajectory adjustments, changing orbit altitude and inclination (the angle of the orbit with respect to the planet's equator), and braking (for getting into orbit around another planet when arriving there with too high velocity from an interplanetary transfer flight). Smaller thrusters, often on the order of a couple of tens of newton force, are used for attitude control and delicate maneuvering (with 1 newton being equivalent to the force that gravity exerts on a 100-gram [0.2-pound] mass on Earth's surface). The mass of the required propellant, rocket thrusters, tanks, pipes, and valves often comprises a large part of the total spacecraft mass.

The Venus Express spacecraft of the ESA, for example, had a total mass of about 1270 kg (2800 pounds) when it was sent on its way. No less than 570 kg (1260 pounds) of this was propellant, while the propulsion hardware had a mass of 60 kg (130 pounds); the propulsion subsystem thus accounted for about 50 percent of the total mass!

Even when orbit adjustments are not needed, the attitude control (stabilization) and orbit maintenance of satellites requires a lot of propellant. About 30 percent of the total mass of a typical geostationary communications satellite with a lifetime of 15 years consists of propellant for so-called station keeping.

Electric Propulsion

There is a more mass-efficient type of propulsion that requires much less propellant for the same spacecraft and mission. Rather than ejecting hot gases that are products of a combustion process, electric propulsion systems eject charged particles using electromagnetic forces. In an "ion engine" the atoms of an inert gas, usually xenon, are ionized and shot out at a much higher velocity than in a normal rocket engine; while an engine burning liquid propellants may shoot out hot gases at 4.5 kilometers per second (3 miles per second), an ion engine expels its charged atoms at more than four times this speed. This makes ion engines much more efficient, giving the same impulse and therefore enabling the same increase in spacecraft orbital velocity or rotational velocity management (in the case of attitude control) for much less propellant. Ion engines are already widely used as attitude control thrusters for large communications satellites and are now also employed as a means of propulsion for interplanetary missions (Fig. 2.6).

However, electric propulsion also has disadvantages. In conventional

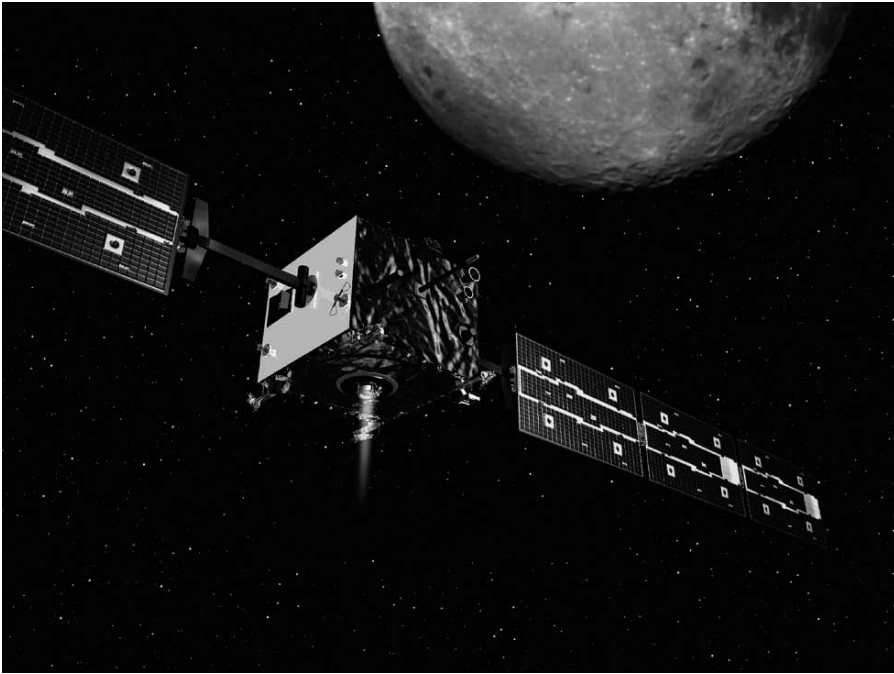


Figure 2.6: Artist's impression of ESA's SMART-1 spacecraft, which tested solar-electric propulsion by using it to fly to the Moon. (Courtesy of ESA.)

rocket engines the energy that propels the gases out of the nozzle at high speed comes from the combustion of chemical propellants. An ion engine requires a strong magnetic field to charge and accelerate gas atoms, and for that it needs electricity. This is supplied by the Sun through the solar arrays, which is why the concept is usually referred to as solar electric propulsion. It means that spacecraft with electric propulsion require larger and thus heavier solar arrays than similar probes with chemical propulsion systems.

More serious is the problem that ion engines can produce only tiny thrust levels, on the order of the weight of a sheet of paper. Electric propulsion, therefore, can be used only in space; on Earth an ion engine is not even capable of lifting its own weight, let alone a spacecraft. The extremely low thrust means that a spacecraft with ion engines can manage only very small acceleration levels, on the order of a fraction of a millimeter (a hundredth of an inch) per second every second. To increase the velocity by 1 meter per second can take more than an hour. Interplanetary probes using electric propulsion thus take much more time to reach their target, which increases operations costs and the wear and tear on spacecraft equipment. Moreover, the tiny thrust levels mean that ion engines have to run for much longer

durations than conventional engines, which increases the risk of failure. The ESA's SMART-1 spacecraft, a lunar satellite whose main mission was to flight test solar electric propulsion for future deep space missions, took 16 months and 332 ever-widening orbits around Earth to reach the moon. With some short boosts from a conventional rocket engine it would have taken a similar probe only a couple of days to get there.

With respect to conventional propulsion systems, solar-electric systems trade high thrust levels for increased efficiency and therefore lower propellant consumption, resulting in a lower propellant mass (and thus a lower total spacecraft mass or the possibility to incorporate more scientific equipment). Ion engines are thus very efficient, but using them means considerably stretching the duration of interplanetary transfers and orbit adjustments, and precludes the use of quick and sudden maneuvers. This makes solar electric propulsion fairly useless for crewed space missions, which require transfers that are as short as possible to limit adverse physiological and psychological effects and to minimize the amount of water, air, and food needed onboard.

Solar Sailing

Using even less propellant than solar electric propulsion, zero in fact, is solar sailing. Rather than converting the Sun's radiation into electricity to run a rocket, a solar sail uses solar energy directly. Solar sails are large, ultralight, mirror-like sheets of extremely thin foil. As light is reflected, the light photons transfer some momentum to the sail as they "bounce" away. The result is that the light exerts a tiny force on the solar sail (a bit like making a toy car with a sail on top move by shooting little balls at it). The push is extremely small, less than a kilogram of force per square kilometer (0.8 pounds per square mile), so an enormous surface is needed to get any significant acceleration out of it. Somewhat like electric propulsion, the weak push acts continuously so that eventually a solar sail spacecraft could attain speeds several times faster than possible with traditional rockets.

The continuous force of sunlight acting on a solar sail could also be used to put spacecraft into very special orbits that are not strictly limited to the orbital mechanics rules of Newton and Kepler. Instead of following a normal orbit, a very light solar sail may "hover" in a fixed position with respect to the Sun and the stars, by balancing the Sun's gravity pull and light pressure push. In a similar way a solar sail may remain in a fixed position over the North or South Hemisphere of Earth, something that for normal satellites is only possible over the equator, in GEO (Fig. 2.7).

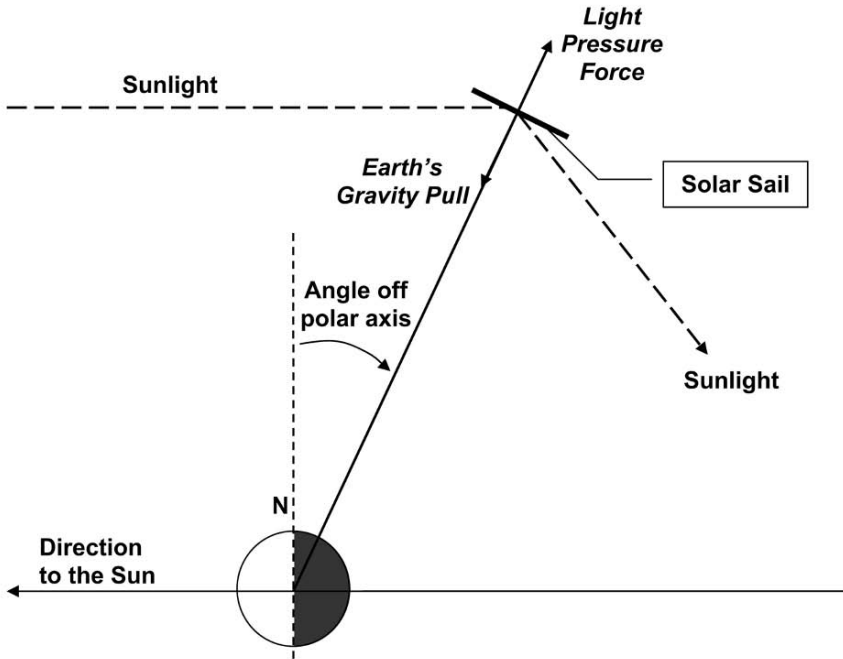


Figure 2.7: A solar sail could balance the Sun's gravity and light pressure to remain in a fixed position over Earth at high latitudes, rather than follow a conventional orbit.

A big disadvantage, however, is that the Sun needs to be close enough for the sail to receive enough light; the further out into the solar system, the lower the acceleration. Beyond the orbit of Mars acceleration levels are too low for the practical use of solar sails (which does not mean solar sails cannot fly any further; as long as they pick up enough speed in the inner solar system they can fly well beyond Mars). Powerful lasers on Earth could help push a solar sail, but a laser also loses its usefulness over long distances because the small divergence of the initially tight beam becomes apparent. Part of the laser energy then flies past the solar sail and does not contribute to the propulsive force. Another big challenge for solar sailing is how to fold the vast surfaces of ultrathin foil in such a way that it fits inside the payload fairing of a launcher, and can still be deployed without damage once in space. Attitude control of flexible solar sails is also still a challenge. Finally, travel times with huge solar sails from one Earth orbit to another or to other planets are very long.

Both NASA and ESA have made some deployment tests of small solar sails on Earth, and are studying demonstration missions to test deployment in Earth orbit. The Planetary Society, an organization of space enthusiasts in

the United States, has already attempted to launch a privately financed test model, Cosmos 1. The spacecraft was designed and built together with the Russian Lavochkin Association and the Russian Space Research Institute. Unfortunately, the launch with a Volna rocket in 2005 failed and Cosmos 1 was destroyed, but the Planetary Society is preparing for a second try.

Another Way Forward

All in all, it appears there is a definite need for a more efficient and much less costly means of getting into orbit, and for more efficient ways of reaching other planets or changing orbits—methods that do not require huge amounts of propellant or take incredibly long periods of time to get up to speed and reach a destination. Several tether applications do enable quick spacecraft accelerations, by electrodynamically propelling or even throwing satellites into higher orbits.

Many space tether concepts are also fully reusable, in contrast to conventional launchers that leave a lot of waste, such as spent rocket stages falling back to Earth (sometimes with leftover toxic propellant on board) or remaining in orbit as space debris. Moreover, rockets expel gases and small particles into the atmosphere. With the current low launch rate, the effect on the environment is negligible, but if we require more frequent access to space in the future, then pollution may become an important issue. Tethers enable more sustainable spaceflight than our current propulsion technology (the United Nations defines “sustainable” as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”).

The space elevator concept has the potential to cause a revolution in human history. We have been living at the bottom of a gravity well up until now, and we only recently acquired the technology to climb out once in a while at high cost. A space elevator would provide an easy, regular, and sustainable way out of that well, allowing many people to clamber up and explore, develop, and colonize space ever further. As will be shown in the next chapters, tether technology is a possible solution for many of the most stringent spaceflight constraints.



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