SOLAR SAILS

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A NOVEL APPROACH TO INTERPLANETARY TRAVEL

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Dedicated to:

My parents
Giovanni Vulpetti

Carol, my wife and companion on this life's journey
Les Johnson

My wife, partner, and colleague, C Bangs
Gregory L. Matloff

Foreword

At the time of writing, a true solar sail has yet to be flown in space. Yet despite this, there is tremendous international interest in this exciting and visionary concept. The excitement is captured in this excellent book which contains something for everyone, from a non-mathematical discussion of the principles of solar sailing to a detailed mathematical analysis of solar sail trajectories. More than that, the book places solar sailing in its proper context by providing a discussion of other propulsion technologies and highlights the benefits (and limitations) of solar sailing.

For the lay reader the book provides a complete introduction to, and discussion of, space propulsion. For the professional scientist and engineer it provides a starting point to further explore the uses of solar sailing. For all readers, it should inspire. Solar sailing is perhaps the most captivating form of spacecraft propulsion currently under development. While other advanced concepts will not make the jump from imagination to reality for many years to come, solar sailing promises to become a reality in the near term. Read this book, and then tell you friends and colleagues that some day very soon we may be literally sailing through space on a sun beam.

Colin McInnes
University of Strathclyde, Glasgow, 31 May 2007

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Preface

This is one of the first books devoted to space solar sailing written in the 21st century. It is intended for both space enthusiasts (nonexperts) and those who are more technically trained. Never before has solar-sail propulsion been so close to being demonstrated via real missions around the Earth. After a number of preliminary tasks in space, the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the Japan Aerospace Exploration Agency (JAXA) are now designing real experimental missions to be accomplished by the first generation of solar-sail technology. Historically, we mention three serious attempts that began the solar-sail era in space. First, the solar-sail mission to the comet Halley, fostered by JPL in the 1970s, was ultimately not approved by NASA. In 1997, the precursor sailcraft Daedalus, fostered by ESA/ESTEC, received no approval from the ESA Council. In 2005, the small experimental sailcraft Cosmos-1, sponsored by the Planetary Society (U.S.), was not successful due to the failure of the Russian submarine-based launch vehicle. However, despite these aborted attempts, the problems these mission planners dealt with provided a serious base for many further studies and serious technology development activities. Strangely enough, following these "failed" attempts, theoretical research and ground demonstrations of small-sail deployment increased in number. The benefits of solar sailing are so clear and compelling that national space agencies and private organizations could not miss the chance to make a quality jump forward in space propulsion, potentially enabling exciting new science and exploration missions throughout the solar system.

This book has four parts. The first three parts are intended for the nontechnical reader who wishes to learn more about one of the most intriguing aspects of near and medium-term spaceflight: solar-sail propulsion and the missions that solar sailing will enable. These parts are completely self-consistent and self-sufficient. Various "technical boxes" have been inserted to provide the interested reader with a more technical or historical explanation. The fourth part contains the supporting mathematics, intended for more technical readers, and in particular for undergraduate students. A glossary is provided at the end of the book containing definitions of many key terms. Many topics discussed in this book are technical in nature yet the fundamental principles may be readily understood by even the most casual reader. Regardless of the reader's general interest level, the authors have made significant efforts to achieve the following goals:

- Technical correctness in all aspects of the book
- Completeness of the main topics and subtopics within the limits of a reasonably sized book
- Timeliness, as the designs, realizations, and information related to space sailing were updated up to the moment the manuscript was sent to the publisher.

Part I, Space Engines: Past and Present, contains five chapters. Chapter 1 introduces the fundamentals of spacecraft propulsion. Chapter 2 describes how rocket engines work. Chapter 3 addresses the problems and limitations of chemical, nuclear, and ion rocket propulsion. Chapter 4 considers various non-rocket technologies that may be used for space propulsion. Chapter 5 introduces the sailing concept by starting from afar—about 45 centuries ago in the Mediterranean Sea, where the Phoenicians invented a very efficient way for navigating the seas. Some of their intuitions still hold for both sailing earthly seas and in space. The authors then summarize how conventional wind sailboats work. From related physical phenomena, consider space sails—their operational analogies and their first important differences with respect to wind-powered sails. The authors subsequently introduce the amazing nature of light and its progressive scientific comprehension that began just a few centuries ago.

Part II, Space Missions by Sail, contains five chapters. Chapter 6 states that space sailing is "free," deriving propulsion from either sunlight or the solar wind. Differences between the concepts of sunlight-driven solar sails, magnetic sails, plasma sails, and electric sails are discussed. Chapter 7 is devoted to the concept of sail spacecraft, or sailcraft, and how they drive the design of a completely new class of spacecraft. Also, the concept of micro-sailcraft is introduced. Chapter 8 compares rocket propulsion and (photon) solar-sail propulsion from many practical viewpoints: design, complexity, risks, mission requirements, and range of application. Chapter 9 is devoted to exploring and developing space by sailcraft. Near-term, medium-term, long-term, and interstellar missions are discussed; sailships to other stars are given a special emphasis. Chapter 10 describes different ways of "riding" a beam of light. Sailing via laser or microwaves is discussed and compared with the so-called particle-beam sail propulsion.

Part III, Construction of Sailcraft, contains four chapters. Chapter 11 tackles the problem of designing a solar sail. There exist different sail types according to their mission aims and stabilization modes. Maneuvering a solar sail is a fundamental operation in space. This chapter explains what spacecraft attitude is and the various sail attitude control methods that may be used. Chapter 12 deals with the problem of building a sailcraft by using today's technologies or emerging technologies for tomorrow's high-performance space sailing missions. After exploring the current policies for the first solar-sail missions, the chapter introduces nanotechnology fundamentals and some of its expected features. The chapter ends by stressing what one may conceive beyond nanotechnology—a science-fiction realm indeed. Chapter 13 discusses the advancements made to date, starting from the pioneering sail/sailcraft designs and the role of the various national space agencies, and concludes with past and current private initiatives and collaborations. Chapter 14 discusses the future plans for solar sailing in the U.S., Europe, and Japan.

Part IV, Space Sailing: Some Technical Aspects, is intended for more technical readers, in particular for undergraduate students in physics, engineering, and mathematics. Although the math has been kept simple, a modest background in physics and elementary calculus is advisable. The chapters in this section contain concepts, explanations and many figures to more technically describe sailcraft missions and their feasibility. Chapter 15 is devoted to the space sources of light, and the Sun in particular. After basic optical definitions and concepts, emphasis is put on the solar electromagnetic radiation spectrum, its variability, and the measurements made in the space era by instruments on some solar-physics satellites. Total solar irradiance, a fundamental element in solar sailing, is discussed widely. Chapter 16 starts from the heliocentric and sailcraft frames of reference and shows how to get the inertial-frame thrust acceleration from the lightness vector, defined in the sailcraft frame, through momentum-transfer phenomena. The main features of the sailcraft acceleration are highlighted via reference accelerations of particular physical meaning. Chapter 17 is the central piece of Part IV. The authors show the class of sailcraft trajectories via several technical plots. Some trajectories have been designed in the past decades, some others were investigated in the first years of this century, and others have been calculated specifically for this book by means of modern (and very complex) computer codes. After a discussion of the formal sailcraft motion vector equation, the reader is introduced to general Keplerian orbits. Then, interplanetary transfer trajectories to planets are discussed. Non-Keplerian orbits are explained, as are many-body orbits and their main characteristics, and fast and very-fast solar sailing. Chapter 18 deals with the important and delicate matter of the impact of the space environment on the whole sail system design. The reader is introduced to the main environmental problems that affect a solar-sail mission, especially if it is close to the Sun.

Acknowledgments

The authors owe special thanks to their wonderful families for the comprehension, the patience, and even some very fine suggestions received in the almost two years of our efforts. It is not an easy thing to go home in the evening from our respective institutes/companies and then after a fast dinner to work on a demanding book at night and on many, many weekends.

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Particular thanks go to the publisher, Clive J. Horwood, the copy editor, and Praxis Publishing, for their precious work—expertise, suggestions to the authors, full willingness to exchanging ideas, patience, to cite just a few—that transformed very high technical areas of spaceflight into a readable book.

Giovanni Vulpetti, Les Johnson, and Greg Matloff
May 2007

I

Space Engines: Past and Present

An Historical Introduction to Space Propulsion

1

We'll never know when the dream of spaceflight first appeared in human consciousness, or to whom it first appeared. Perhaps it was in the sun-baked plains of Africa or on a high mountain pass in alpine Europe. One of our nameless ancestors looked up at the night sky and wondered at the moving lights in the heavens.

Was the Moon another world similar to Earth? And what were those bright lights—the ones we call planets—that constantly change position against the background of distant stellar luminaries. Were they gods and goddesses, as suggested by the astrologers, or were they sisters to our Earth?

And if they were other worlds, could we perhaps emulate the birds, fly up to the deep heavens and visit them? Perhaps it was during a star-strewn, Moon-illuminated night by the banks of the river Nile or on the shores of the Mediterranean, as early sailing craft began to prepare for the morning trip upriver or the more hazardous sea voyage to the Cycladic Isles, that an imaginative soul, watching the pre-dawn preparations of the sailors, illuminated by those strange celestial beacons, might have wondered: If we can conquer the river and sea with our nautical technology, can we reach further? Can we visit the Moon? Can we view a planet close up?

It would be millennia before these dreams would be fulfilled. But they soon permeated the world of myth.

A Bronze-Age Astronaut

These early ponderings entered human mythology and legend. According to one Bronze-Age tale, there was a brilliant engineer and architect named Daedalus who lived on the island of Crete about 4000 years ago. For some offense, he and his son, Icarus, were imprisoned in a tower in Knossos, which was at that time the major city in Crete.

Being fed on a diet of geese and illuminating their quarters with candles, Daedalus and Icarus accumulated a large supply of feathers and wax. Being a

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brilliant inventor, Daedalus fashioned two primitive hang gliders. Wings could be flapped so that the father and son could control their craft in flight.

It's not clear what their destination would be. One version of the story has the team attempting the long haul to Sicily. Another has them crossing the more reasonable 100-kilometer distance to the volcanic island of Santorini. It's interesting to note that a human-powered aircraft successfully completed the hop between Crete and Santorini only a few years ago, thereby emulating a mythological air voyage of the distant past.

Daedalus, being more mature, was cautious and content to be the first aviator. The youthful, headstrong Icarus was somewhat more ambitious. Desiring to become the first astronaut, he ignored his father's pleas and climbed higher and higher in the Mediterranean sky. Unlike modern people, the Bronze-Age Minoans had no concept of the limits of the atmosphere and the vastness of space. Icarus therefore flapped his wings, climbed higher, and finally approached the Sun. The Sun's heat melted the wax; the wings came apart. Icarus plunged to his death as his father watched in horror.

A few thousand years passed before the next fictional physical space flight was attempted. But during this time frame, several Hindu Yogi are reputed to have traveled in space by methods of astral projection.

Early Science-Fiction; The First Rocket Scientist

Starting with Pythagoras in the 6th century B.C., classical scholars began the arduous task of charting the motions of the Moon and planets, and constructing the first crude mathematical models of the cosmos. But they still had no idea that Earth's atmosphere did not pervade the universe. In what might be the first science-fiction novel, creatively entitled *True History*, the 2nd-century A.D. author Lucian of Samosata used an enormous waterspout to carry his hero to the Moon. Other authors assumed that flocks of migratory geese (this time with all their feathers firmly attached) could be induced to carry fictional heroes to the celestial realm.

What is very interesting is that all of these classical authors chose to ignore an experiment taking place during the late pre-Christian era that would pave the way to eventual cosmic travel. Hero of Alexandria, in about 50 B.C., constructed a device he called an aeolipile. Water from a boiler was allowed to vent from pipes in a suspended sphere. The hot vented steam caused the sphere to spin, in a manner not unlike a rotary lawn sprinkler. Hero did not realize what his toy would lead to, nor did the early science-fiction authors. Hero's aeolipile is the ancestor of the rocket.

Although Westerners ignored rocket technology for more than 1000 years, this was not true in the East. As early as 900 A.D., crude sky rockets were in use in China, both as weapons of war and fireworks.

Perhaps He Wanted to Meet the ''Man in the Moon''

Icarus may have been the first mythological astronaut, but the first legendary rocketeer was a Chinese Mandarin named Wan Hu. Around 1000 A.D., this wealthy man began to become world-weary. He asked his loyal retainers to carry him, on his throne, to a hillside where he could watch the rising Moon. After positioning their master facing the direction of moonrise, the loyal servants attached kites and strings of their most powerful gunpowder-filled skyrockets to their master's throne.

As the Moon rose, Wan Hu gave the command. His retainers lit the fuse. They then ran for cover. Wan Hu disappeared in a titanic explosion. More than likely, his spaceflight was an elaborate and dramatic suicide. But who knows? Perhaps Wan Hu (or his fragments) did reach the upper atmosphere.

In the 13th century A.D., the Italian merchant-adventurer Marco Polo visited China. In addition to samples of pasta, the concept of the rocket returned west with him.

In post-Renaissance Europe, the imported rocket was applied as a weapon of war. It was not a very accurate weapon because the warriors did not know how to control its direction of flight. But the explosions of even misfiring rockets were terrifying to friend and foe alike.

By the 19th century, Britain's Royal Navy had a squadron of warships equipped with rocket artillery. One of these so-called "rocket ships" bombarded America's Fort McHenry during the War of 1812. Although the fort successfully resisted, the bombardment was immortalized as "the rocket's red glare" in the American national anthem, "The Star Spangled Banner."

The 19th century saw the first famous science-fiction novels. French writer Jules Gabriel Verne wrote *From the Earth to the Moon* (1865), *Twenty Thousand Leagues under the Sea* (1869), *Around the Moon* (1870), and *Around the World in Eighty Days* (1873). Particularly intriguing concepts can be found especially in the latter two books. In *Around the Moon*, Captain Nemo discovers and manages a mysterious (nonchemical) "energy", which all activities and motion of Nautilus depend on. In *Around the World in Eighty Days*, Phileas Fogg commands the crew to use his boat structure materials (mainly wood and cloth) to fuel the boat steam boiler and continue toward England. A rocket ship that (apart from its propellant) burns its useless materials progressively is an advanced concept indeed! Jules Verne is still reputed to be one of the first great originators of the science-fiction genre.

In 1902, French director Georges Méliès realized the cinematographic version of Verne's novel *From the Earth to the Moon*: in his film, *A Trip to the Moon*. Many other films describing men in space followed. For his film, Méliès invented the technique called "special effects." Thus, science-fiction cinema was born and consolidated in the first years of the 20th century, just before the terrible destruction caused by World War I.

It is surprising that science-fiction authors of the 17th to 19th centuries continued to ignore the rocket's space-travel potential, even after its military application. They employed angels, demons, flywheels, and enormous naval guns to break the bonds of Earth's gravity and carry their fictional heroes skyward. But (with the exception of Cyrano de Bergerac) they roundly ignored the pioneering efforts of the early rocket scientists.

The Dawn of the Space Age

The first person to realize the potential of the rocket for space travel was neither an established scientist nor a popular science-fiction author. He was an obscure secondary-school mathematics teacher in a rural section of Russia. Konstantin E. Tsiolkovsky (Fig. 1.1), a native of Kaluga, Russia, may have begun to ponder the physics of rocket-propelled spaceflight as early as the 1870s. He began to publish his findings in obscure Russian periodicals before the end of the 19th century. Tsiolkovsky pioneered the theory of various aspects of space travel. He considered the potential of many chemical rocket fuels, introduced the concept of the staged rocket (which allows a rocket to shed excess weight as it climbs), and was the first to investigate the notion of an orbiting space station. As will be discussed in later chapters, Tsiolkovsky was one of the first to propose solar sailing as a non-rocket form of space travel. Soviet Russia's later spaceflight triumphs

Figure 1.1. Romanian postage stamp with image of Tsiolkovsky, scanned by Ivan Kosinar. From Physics-Related Stamps Web site: www.physik.uni-frankfort.de/~jr/physstamps.html

Figure 1.2. Hermann Oberth. (Courtesy of NASA)

have a lot to do with this man. Late in his life, during the 1930s, his achievements were recognized by Soviet authorities. His public lectures inspired many young Russians to become interested in space travel. Tsiolkovsky, the recognized father of astronautics, died in Kaluga at the age of 78 on September 19, 1935. He received the last honors by state funeral from the Soviet government. In Kaluga, a museum honors his life and work.

But Tsiolkovsky's work also influenced scientists and engineers in other lands. Hermann Oberth (Fig. 1.2), a Romanian of German extraction, published his first scholarly work, *The Rocket into Interplanetary Space,* in 1923. Much to the author's surprise, this monograph became a best-seller and directly led to the formation of many national rocket societies. Before the Nazis came to power in Germany and ended the era of early German experimental cinema, Oberth created the first German space-travel special effects for the classic film *Frau Im Mund* (Woman in the Moon).

Members of the German Rocket Society naively believed that the Nazi authorities were seriously interested in space travel. By the early 1940s, former members of this idealistic organization had created the first rocket capable of reaching the fringes of outer space—the V2. With a fueled mass of about 14,000 kilograms and a height of about 15 meters, this rocket had an approximate range of 400 kilometers and could reach an altitude of about 100 kilometers. The payload of this war weapon reached its target at a supersonic speed of about 5000 kilometers per hour.

Instead of being used as a prototype interplanetary booster, the early V2s

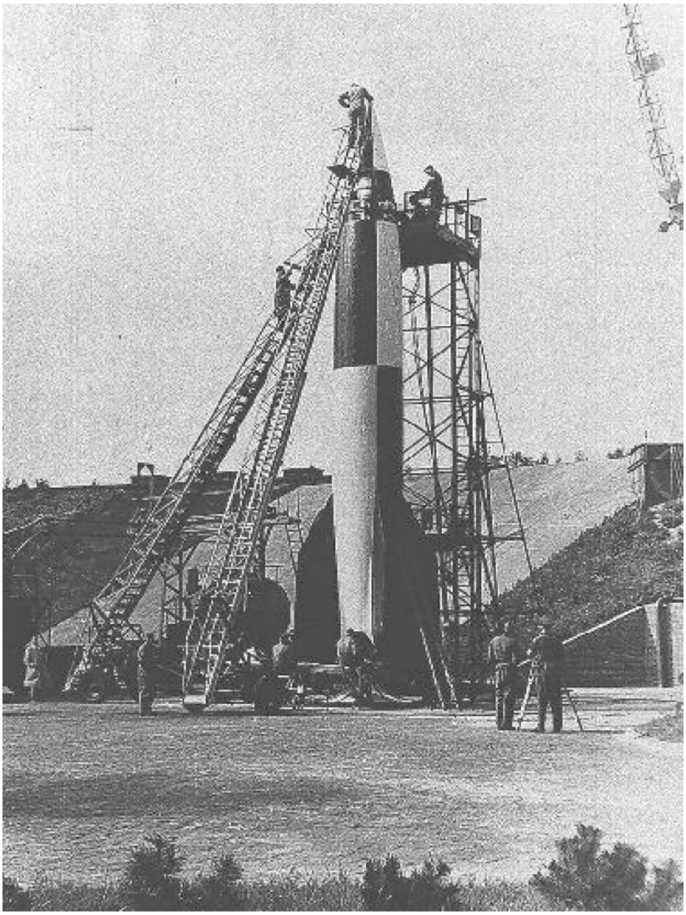

Figure 1.3. German V2 on launch pad. (Courtesy of NASA)

(Fig. 1.3) rained down upon London, causing widespread property damage and casualties. Constructed by slave laborers in underground factories, these terror weapons had the potential to change the outcome of World War II. Fortunately, they did not.

An enlarged piloted version of the V2, called the A-10, was on the drawing boards at war's end. The A-10 could have boosted a hypersonic bomber on a trajectory that skipped across the upper atmosphere. Manhattan could have been bombed in 1946 or 1947, more than five decades before the terrorist attacks of September 11, 2001. After dropping their bombs, German skip-bomber flight crews might have turned southward toward Argentina, where they would be safely out of harm's way until the end of the war.

But America had its own rocket pioneer, who perhaps could have confronted this menace from the skies. Robert Goddard (Fig. 1.4), a physics

Figure 1.4. Robert Goddard. (Courtesy of NASA)

professor at Clark University in Massachusetts, began experimenting with liquid-fueled rockets shortly after World War I.

Goddard began his research with a 1909 study of the theory of multistage rockets. He received more than 200 patents, beginning in 1914, on many phases of rocket design and operation. He is most famous, though, for his experimental work. Funded by the Guggenheim Foundation, he established an early launch facility near Roswell, New Mexico. During the 1920s and 1940s, he conducted liquid-fueled rocket tests of increasing sophistication. One of his rockets reached the then-unheard-of height of 3000 meters! Goddard speculated about small rockets that could reach the Moon. Although he died in 1945 before his ideas could be fully realized, his practical contributions led to the development of American rocketry.

In the postwar era, the competition between the United States and the Soviet Union heated up. One early American experiment added an upper stage to a captured German V2 (Fig. 1.5). This craft reached a height of over 400 kilometers. An American-produced V2 derivative, the Viking (Fig. 1.6) was the mid-1950's precursor to the rockets that eventually carried American satellites into space.

After Russia orbited Sputnik 1 in 1957, space propulsion emerged from the back burner. Increasingly larger and more sophisticated chemical rockets were developed—first by the major space powers, and later by China, some European countries, Japan, India, and Israel. Increasingly more

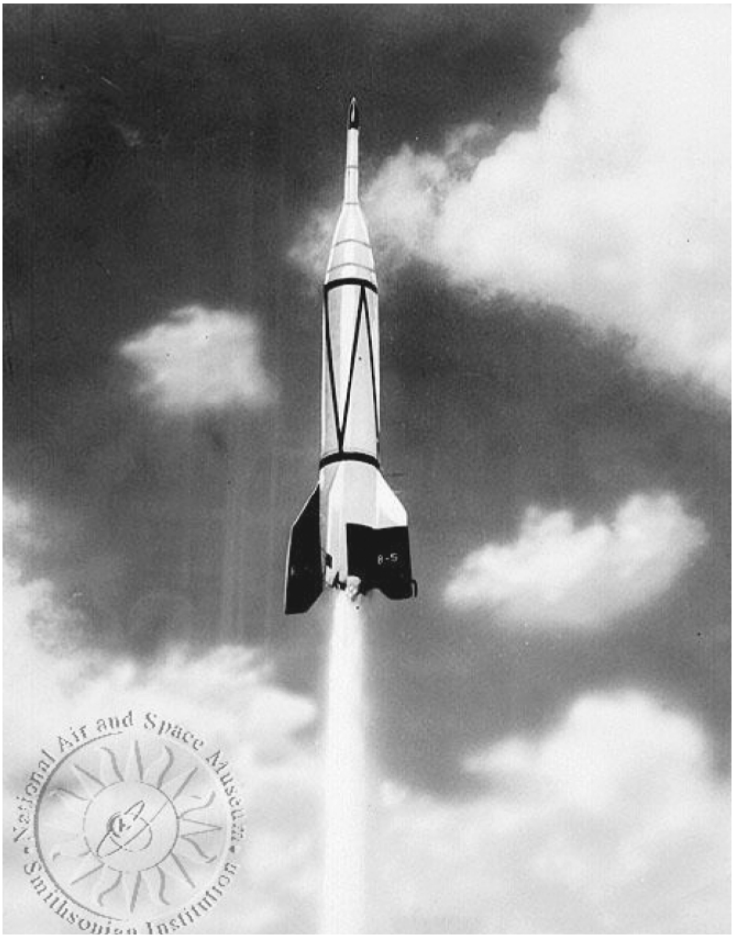

Figure 1.5. A two-stage V2, launched by the United States in the postwar era. (Courtesy of NASA)

massive spacecraft, all launched by liquid or solid chemical boosters, have orbited Earth, and reached the Moon, Mars, and Venus. Robots have completed the preliminary reconnaissance of all major solar system worlds and several smaller ones. Humans have lived in space for periods longer than a year and trod the dusty paths of Luna (the Roman goddess of the Moon).

We have learned some new space propulsion techniques—low-thrust solar-electric rockets slowly accelerate robotic probes to velocities that chemical rockets are incapable of achieving. Robotic interplanetary explorers apply an elaborate form of gravitational billiards to accelerate without rockets at the expense of planets' gravitational energy. And we

Figure 1.6. A V2 derivative: the American Viking rocket. (Courtesy of NASA)

routinely make use of Earth's atmosphere and that of Mars to decelerate spacecraft from orbital or interplanetary velocities as they descend for landing.

But many of the dreams of early space travel enthusiasts remain unfulfilled. We cannot yet sail effortlessly through the void, economically tap interplanetary resources, or consider routine interplanetary transit. Human habitation only extends as far as low-Earth orbit, a few hundred kilometers above our heads, and our preliminary in-space outposts can only be maintained at great expense. And the far stars remain beyond our grasp. For humans to move further afield in the interplanetary realm as we are preparing to do in the early years of the 21st century, we need to examine alternatives to the chemical and electric rocket. The solar-photon sail—the subject of this book—is one approach that may help us realize the dream of a cosmic civilization.

Further Reading

Many sources address the prehistory and early history of space travel. Two classics are the following: Carsbie C. Adams, *Space Flight: Satellites, Spaceships, Space Stations, Space Travel Explained* (1st ed.), McGraw-Hill, New York, 1958. http://www.rarebookcellar.com/; Arthur C. Clarke, *The Promise of Space*, Harper & Row, New York, 1968.

The Minoan myth of Daedalus and Icarus is also widely available. See, for example, F. R. B. Godolphin, ed., *Great Classical Myths*, The Modern Library, New York, 1964.

Many popular periodicals routinely review space-travel progress. Two of these are the following: *Spaceflight*, published by the British Interplanetary Society; and *Ad Astra*, published by the U.S. National Space Society.

2 The Rocket: How It Works in Space

The rocket is a most remarkable device. Its early inventors could not have guessed that it would ultimately evolve into a device capable of propelling robotic and human payloads through the vacuum of space. In fact, the rocket actually works better in a vacuum than in air!

To understand rocket propulsion, we must first digress a bit into the physics of Isaac Newton.

Newtonian Mechanics and Rocket Fundamentals

A quirky and brilliant physicist, Isaac Newton framed, during the 17th century, the laws governing the motion of macroscopic objects moving at velocities, relative to the observer, well below the speed of light (300,000 kilometers per second). This discipline is called "kinematics" since it deals with motion in itself, not the causes of it. This type of physics, aptly called "Newtonian mechanics" works quite well at describing the behavior of almost all aspects common to everyday human experience, even space travel. It does not, however, accurately describe the motion of objects that are moving very fast.

To investigate kinematics of high-velocity objects moving at 20,000 kilometers per second or faster, we need to apply the results of Einstein's theory of special relativity. To consider the motion (and other properties) of microscopic objects—those much smaller than a pinhead or dust grain—we need to apply the principles of quantum mechanics. Both relativity and quantum mechanics were developed three centuries after Newton.

For macro-sized rockets moving at velocities measured in kilometers or tens of kilometers per second, newtonian physics is quite adequate. The most relevant aspects of kinematics to rocket propulsion are inertia, velocity, acceleration, and linear momentum. We will consider each of these in turn.

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Inertia—Objects Resist Changes in Motion

Iron-Age scholars such as Aristotle assumed that objects move the way they do because such motion is in their nature. Although not quantifiable, such a conclusion was an improvement over the earlier Bronze-Age notion that a deity (or deities) controlled the motions of all objects.

Newton's first step in quantifying the concept of motion was to introduce the principle of inertia. All mass contains inertia—the greater the mass, the greater the inertia. Essentially, an object with mass or inertia tends to resist changes in its motion. The only way to alter the object's velocity is to act upon the object with a force. This principle is often referred to as Newton's first law; it has represented the birth of "dynamics," namely, the description of a body's motion with the inclusion of the causes that determine it.

Force and a Most Influential Equation

As a point of fact, what really separated Newton from earlier kinematicists was his elegant and most successful mathematical representation of the force concept. No longer would forces be in the province of mysterious (and perhaps) unknowable essences or natures; no longer would gods or goddesses move things at their whim. Instead, an entire technological civilization would arise based on such simple, and easily verifiable equations as Newton's relationship among force (F), mass (M), and acceleration (A).

If we are working in the MKS or standard set of units, forces are measured in units of newtons (N), masses are in kilograms (kg), and accelerations—the rate at which velocities change with time—are in meters per square second (m/s^2). The famous force equation, which is called Newton's second law, is written as follows:

$$F = MA, \tag{1}$$

or Force = Mass times Acceleration.

Let's consider what this means in practice. If a 10-newton force acts on a 1-kilogram mass, Equation 10 reveals that the force will accelerate the mass by 10 meters per square second. This force will just lift the object from the ground if it is directed upward, since Earth's gravitational acceleration (g) is 9.8 meters per square second. If the same force acts upon an object with a mass of 10 kilograms, the acceleration of the mass imparted by the force will be 1 meter per square second.

To apply Newton's second law successfully to any mode of propulsion, you must do two things. You must maximize the force and minimize the mass of the object you wish to accelerate.

Actions and Reactions

Forces, velocities, and accelerations are representatives of a type of quantity called "vectors." Unlike "scalars," which only have magnitude, vector quantities have both magnitude and direction.

We unconsciously apply the concepts of scalars and vectors all the time. Let's say that we wish to fly between London and New York. We first book a flight on an Airbus or Boeing jetliner, since such a craft can cruise at speeds of around 1000 kilometers per hour. But to minimize travel time between London and New York, we book a flight traveling in the direction of New York City—a jetliner traveling in the direction of Sydney, for example, would not do much to minimize our travel time.

Now let's examine the case of a baseball or cricket player hitting a ball with a bat. The bat is swung to impart a force on the ball, which (if all goes well from the viewpoint of the batter or bowler) flies off in the desired direction at high speed. As high-speed videotapes reveal, bats sometimes crack during the interaction. This is because a "reaction" force is imparted to the bat by the struck ball.

If you've ever fired a rifle or handgun, you've experienced action and reaction force pairs. An explosion accelerates the low-mass bullet out the gun muzzle at high speed. This is the action force. The recoil of the weapon against your shoulder—which can be painful and surprising if you are not properly braced against it—is the reaction force.

Newton's third law considers action–reaction force pairs. For every action, Newton states, there is an equal and opposite reaction. The action and reaction forces are equal in magnitude but act in opposite directions.

Jets and rockets are representative "action–reaction" propulsion systems. In a jet or chemical rocket, a controlled and contained explosion accelerates fuel to a high velocity. The ejection of this fuel from the engine nozzle is the action member of the force pair. The reaction is an equal force accelerating the engine (and structures connected to it) in the direction opposite the exhaust.

The trick with a successful jet or rocket is to minimize structural mass (and payload) and maximize fuel exhaust velocity.

Linear Momentum: A Conserved Quantity

As first-year college physics students learn, Newton's third law can be used to demonstrate that linear momentum (P) is conserved in any physical system. Linear momentum is a vector quantity, which is defined as the product of mass (M) and velocity (V) and is written $P = MV$. If the chemical reaction in the rocket's combustion chamber increases the expelled fuel's momentum by P_f, conservation of linear momentum requires that the rocket's momentum