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Historical Overview

1.1 Introduction

Before we begin our technical discussion of space flight dynamics, this first chapter will provide a condensed historical overview of the principle contributors and events associated with the development of what we now commonly refer to as *space flight*. We may define space flight as sending a human-made satellite or spacecraft to an Earth orbit or to another celestial body such as the moon, an asteroid, or a planet. Of course, our present ability to launch and operate satellites in orbit depends on knowledge of the physical laws that govern orbital motion. This brief chapter presents the major developments in astronomy, celestial mechanics, and space flight in chronological order so that we can gain some historical perspective.

1.2 Early Modern Period

The fields of astronomy and celestial mechanics (the study of the motion of planets and their moons) have attracted the attention of the great scientific and mathematical minds. We may define the *early modern period* by the years spanning roughly 1500–1800. This time frame begins with the late Middle Ages and includes the Renaissance and Age of Discovery. Figure 1.1 shows a timeline of the important figures in the development of celestial mechanics during the early modern period. The astute reader will, of course, recognize these illuminous figures for their contributions to mathematics (Newton, Euler, Lagrange, Laplace, Gauss), physics (Newton, Galileo), dynamics (Kepler, Newton, Euler, Lagrange), and statistics (Gauss). We will briefly describe each figure's contribution to astronomy and celestial mechanics.

The first major figure is Nicolaus Copernicus (1473–1543), a Polish astronomer and mathematician who developed a solar-system model with the sun as the central body. Galileo Galilei (1546–1642) was an Italian astronomer and mathematician who defended Copernicus' sun-centered (or "heliocentric") solar system. Because of his heliocentric view, Galileo was put on trial by the Roman Inquisition for heresy and spent the remainder of his life under house arrest.

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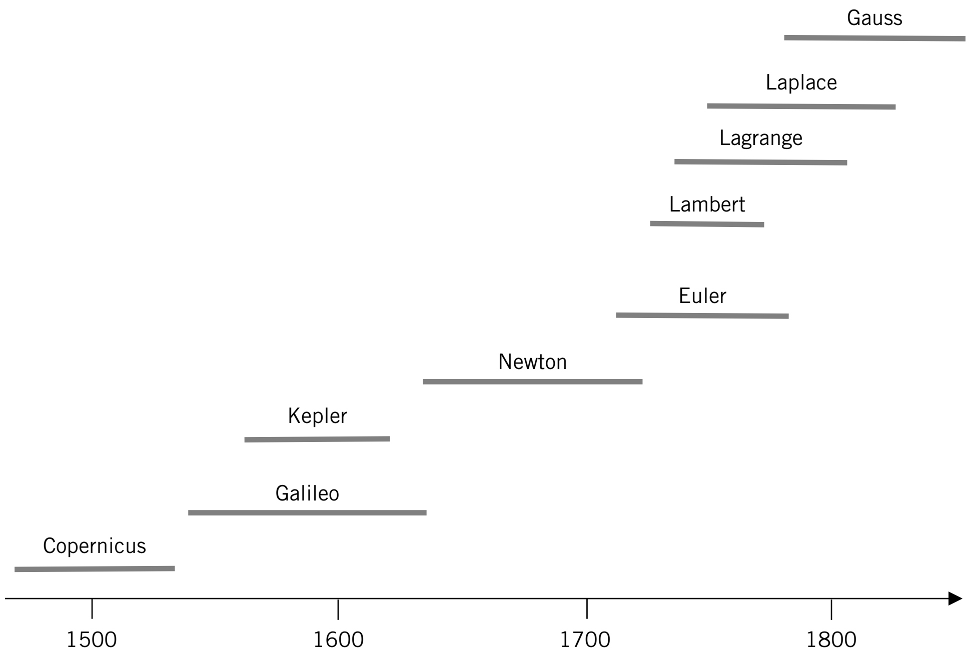

Figure 1.1 Timeline of significant figures in the Early Modern Period.

Johann Kepler (1571–1630) developed the fundamental laws for planetary motion based on astronomical observations of the planet Mars compiled by the Danish nobleman Tycho Brahe (1546–1601). Kepler's three laws are:

1) The orbit of a planet is an ellipse, with the sun located at a focus.
2) The radial line from the sun to the planet sweeps out equal areas during equal time intervals.
3) The square of a planet's orbital period for one revolution is proportional to the cube of the planet's "mean distance" from the sun.

The third law notes the planet's "mean distance" from the sun. In Chapter 2 we will define this "mean distance" as one-half of the length of the major axis of an ellipse. Kepler published his first two laws of planetary motion in 1609 and his third law in 1619. Kepler developed an expression for the time-of-flight between two points in an orbit; this expression is now known as *Kepler's equation*.

Isaac Newton (1642–1727) was an English astronomer, mathematician, and physicist who developed calculus and formulated the laws of motion and universal gravitation. Newton's three laws of motion are:

1) A body remains at rest or moves with a constant velocity unless acted upon by a force.
2) The vector sum of the forces acting on a body is equal to the mass of the body multiplied by its absolute acceleration vector (i.e., $\sum \mathbf{F} = m\mathbf{a}$).
3) When a body exerts a force on a second body, the second body exerts an equal-and-opposite force on the first body.

The first and second laws hold relative to a fixed or inertial reference frame. Newton published the three laws of motion in *Principia* in 1687. Newton's universal law of gravitation states that any two bodies attract one another with a force that is proportional to the product of their masses and inversely proportional to the square of their separation distance. Newton's laws of motion and gravitation explain the planetary motion that Kepler described by geometrical means.

Leonhard Euler (1707–1783), a Swiss mathematician, made many mathematical and scientific contributions to the fields of calculus, mathematical analysis, analytical mechanics, fluid dynamics, and optics. Euler also developed equations that govern the motion of a rotating body; these equations serve as the foundation for analyzing the rotational motion of satellites in orbit. Johann Heinrich Lambert (1728–1777), also a Swiss mathematician, formulated and solved the problem of determining the orbit that passes through two known position vectors with a prescribed transit time. Known today as *Lambert's problem*, its solution provides a method for the orbit-determination process as well as planning orbital maneuvers. Joseph-Louis Lagrange (1736–1813) was an Italian-born mathematician who made significant contributions in analytical mechanics and celestial mechanics, including the determination of equilibrium orbits for a problem with three bodies and the formulation of *Lagrange's planetary equations* for orbital motion. Pierre-Simon Laplace (1749–1827) was a French mathematician who, among his many mathematical contributions, formulated the first orbit-determination method based solely on angular measurements. Carl Friedrich Gauss (1777–1855), a German mathematician of great influence, made significant contributions to the field of orbit determination. In mid-1801 he predicted the orbit of the dwarf planet Ceres using a limited amount of observational data taken before Ceres became obscured by the sun. In late 1801, astronomers rediscovered Ceres just as predicted by Gauss.

1.3 Early Twentieth Century

Let us next briefly describe the important figures in the early twentieth century. It is during this period when mathematical theories are augmented by experimentation, most notably in the field of rocket propulsion. It is interesting to note that the important figures of this period were inspired by the nineteenth century science fiction literature of H.G. Wells and Jules Verne and consequently were tantalized by the prospect of interplanetary space travel.

Konstantin Tsiolkovsky (1857–1935) was a Russian mathematician and village school teacher who worked in relative obscurity. He theorized the use of oxygen and hydrogen as the optimal combination for a liquid-propellant rocket in 1903 (the same year as the Wright brothers' first powered airplane flight). Tsiolkovsky also developed theories regarding rocket propulsion and a vehicle's velocity change – the so-called "rocket equation."

Robert H. Goddard (1882–1945), a US physicist, greatly advanced rocket technology by combining theory and experimentation. On March 16, 1926, Goddard successfully launched the first liquid-propellant rocket. In 1930, Goddard moved his laboratory to New Mexico and continued to develop larger and more powerful rocket engines.

Hermann J. Oberth (1894–1989) was born in Transylvania and later became a German citizen. A physicist by training, he independently developed theories regarding human space flight through rocket propulsion. Oberth was a key figure in the German Society for Space Travel, which was formed in 1927, and whose membership included the young student Wernher von Braun. Von Braun (1912–1977) led the Nazi rocket program at Peenemünde during World War II. Von Braun's team developed the V-2 rocket, the first long-range rocket and the first vehicle to achieve space flight above the sensible atmosphere.

At the end of World War II, von Braun and members of his team immigrated to the US and began a rocket program at the US Army's Redstone Arsenal at Huntsville, Alabama. It was during this time that the US and the Soviet Union were rapidly developing long-range intercontinental ballistic missiles (ICBMs) for delivering nuclear weapons.

1.4 Space Age

On October 4, 1957, the Soviet Union successfully launched the first artificial satellite (Sputnik 1) into an Earth orbit and thus ushered in the *space age*. Sputnik 1 was a polished 84 kg metal sphere and it completed an orbital revolution every 96 min. The US successfully launched its first satellite (Explorer 1) almost 4 months after Sputnik on January 31, 1958. Unlike Sputnik 1, Explorer 1 was a long, tube-shaped satellite, and because of its shape, it unexpectedly entered into an end-over-end tumbling spin after achieving orbit.

Our abridged historical overview of the first half of the twentieth century illustrates the very rapid progress achieved in rocket propulsion and space flight. For example, in less than 20 years after Goddard's 184 ft flight of the first liquid-propellant rocket, Nazi Germany was bombarding London with long-range V-2 missiles. Twelve years after the end of World War II, the USSR successfully launched a satellite into orbit. Another point of interest is that in this short period, rocket propulsion and space flight transitioned from the realm of the singular individual figure to large team structures funded by governments. For example, the US established the National Aeronautics and Space Administration (NASA) on July 29, 1958.

The US and USSR space programs launched and operated many successful missions after the space age began in late 1957. Table 1.1 summarizes notable robotic space missions (i.e., no human crew). A complete list of successful space missions would be quite long; Table 1.1 is not an exhaustive list and instead presents a list of mission "firsts." It is truly astounding that 15 months after Sputnik 1, the USSR sent a space probe (Luna 1) to the vicinity of the moon. Equally impressive is the first successful interplanetary mission (Mariner 2), which NASA launched less than 5 years after Explorer 1. Table 1.1 shows that spacecraft have visited all planets in our solar system and other celestial bodies such as comets and asteroids.

On April 12, 1961, the USSR successfully sent the first human into space when Yuri Gagarin orbited the Earth in the Vostok 1 spacecraft. Less than 1 month later, the US launched its first human into space when Alan Shepard flew a suborbital mission in a Mercury spacecraft. Table 1.2 presents notable space missions with human crews (as with Table 1.1, Table 1.2 focuses on first-time achievements). Tables 1.1 and 1.2 clearly illustrate the accelerated pace of accomplishments in space flight. Table 1.2 shows

Table 1.1 Notable robotic space missions.

Mission	Date	Achievement	Country
Sputnik 1	October 4, 1957	First artificial satellite to achieve Earth orbit	USSR
Luna 1	January 2, 1959	First satellite to reach the vicinity of the moon	USSR
Mariner 2	December 14, 1962	First spacecraft to encounter (fly by) another planet (Venus)	US
Mariner 4	July 14, 1965	First spacecraft to fly by Mars	US
Luna 9	February 3, 1966	First spacecraft to land on another body (moon)	USSR
Luna 10	April 3, 1966	First spacecraft to orbit the moon	USSR
Venera 7	December 15, 1970	First spacecraft to land on another planet (Venus)	USSR
Mariner 9	November 14, 1971	First spacecraft to orbit another planet (Mars)	US
Pioneer 10	December 3, 1973	First spacecraft to fly by Jupiter	US
Mariner 10	March 29, 1974	First spacecraft to fly by Mercury	US
Viking 1	July 20, 1976	First spacecraft to land on Mars	US
Voyager 1	March 1979, November 1980	Fly by encounters with Jupiter, Saturn, and Saturn's moon Titan	US
Voyager 2	January 1986, August 1989	First spacecraft to fly by Uranus and Neptune	US
Galileo	December 8, 1995	First spacecraft to orbit Jupiter	US
Mars Pathfinder	July 4, 1997	First rover on the planet Mars	US
NEAR Shoemaker	February 12, 2001	First spacecraft to land on an asteroid (433 Eros)	US
Cassini-Huygens	July 2004, January 2005	First spacecraft to orbit Saturn (Cassini) and first spacecraft to land on the moon Titan (Huygens)	US and Europe
Stardust	January 16, 2006	First spacecraft to return samples from a comet	US
MESSENGER	March 18, 2011	First spacecraft to orbit Mercury	US
New Horizons	July 14, 2015	First spacecraft to fly by Pluto	US

Table 1.2 Notable space missions with human crews.

Mission	Date	Achievement	Country
Vostok 1	April 12, 1961	First human to reach space and orbit the Earth	USSR
Vostok 6	June 16, 1963	First woman in space	USSR
Voskhod 2	March 18, 1965	First human "spacewalk" outside of orbiting spacecraft	USSR
Gemini 6A	December 15, 1965	First orbital rendezvous	US
Apollo 8	December 24, 1968	First humans to orbit the moon	US
Apollo 11	July 20, 1969	First humans to land and walk on the moon	US
Salyut 1	April 19, 1971	First orbiting space station with crew	USSR
STS-1	April 12, 1981	First flight of a reusable spacecraft (Space Shuttle)	US
International Space Station	November 20, 1998	First multinational space station and largest satellite placed in Earth orbit	Russia, US, Europe, Japan, Canada

Table 1.3 Significant advances in space flight dynamics in the twentieth century.

Researcher(s)	Achievement
Dirk Brouwer Yoshihide Kozai	Developed pioneering work in the field of analytical satellite theory, including the perturbing effects of a non-spherical Earth
Theodore Edelbaum	Obtained analytical optimal trajectory solutions for spacecraft propelled by low-thrust electric propulsion engines
Richard Battin	Developed guidance and navigation theories for lunar and interplanetary spacecraft
Rudolf Kalman	Developed an optimal recursive estimation method (the *Kalman filter*) that has been applied to orbit determination and satellite navigation
W.H. Clohessy and R.S. Wiltshire	Developed closed-form solutions for the motion of a satellite relative to an orbiting target satellite (i.e., orbital rendezvous)
Derek Lawden	Developed theories for optimal rocket trajectories
A.J. Eggers and H.J. Allen Dean Chapman	Obtained analytical solutions for the entry flight phase of a ballistic capsule or lifting spacecraft returning to Earth from space
Robert Farquhar	Conceived of and managed space missions that targeted orbits where the satellite is balanced by the gravitational attracting of two celestial bodies
Ronald Bracewell Vernon Landon	Developed theories regarding the stability of a spinning satellite in orbit
Paul Cefola	Developed the Draper Semianalytical Satellite Theory (DSST) for rapid orbital calculations over a long time period

the very rapid progress in space missions with human crews in the 1960s, culminating with the first Apollo lunar landing on July 20, 1969. To date, three countries have developed human space flight programs: USSR/Russia (1961); US (1961); and China (2003).

We end this chapter with a brief summary of the significant twentieth century figures in the field of space flight dynamics. Table 1.3 presents these figures and their accomplishments. This list is certainly not exhaustive; furthermore, it is difficult to identify single individuals when the tremendous achievements in space flight over the past 60 years involve a large team effort.