LUNAR AND PLANETARY ROBOTIC EXPLORATION MISSIONS IN THE 20TH CENTURY

W. T. HUNTRESS, JR.
Geophysical Laboratory, Carnegie Institution of Washington, Washington, DC, USA
V. I. MOROZ
Institute of Space Research of Russian Academy of Science, Moscow, Russia
I. L. SHEVALEV
Lavochkin Association, Khimki, Moscow Region, Russia

Abstract. The prospect of traveling to the planets was science fiction at the beginning of the 20th Century and science fact at its end. The space age was born of the Cold War in the 1950s and throughout most of the remainder of the century it provided not just an adventure in the exploration of space but a suspenseful drama as the US and USSR competed to be first and best. It is a tale of patience to overcome obstacles, courage to try the previously impossible and persistence to overcome failure, a tale of both fantastic accomplishment and debilitating loss. We briefly describe the history of robotic lunar and planetary exploration in the 20th Century, the missions attempted, their goals and their fate. We describe how this enterprise developed and evolved step by step from a politically driven competition to intense scientific investigations and international cooperation.

1. Opening the Space Age

One of the most exciting developments in the 20th Century has been the opening of the space frontier with flights of robotic spacecraft to the Moon and to the planets beyond. This article presents an abbreviated history of this adventure, from its inception with the launch of Luna 1 on January 2, 1959, to the Stardust mission launched on February 7, 1999, the last such spacecraft to be launched in the 20th Century.

The first pioneers of space flight were visionaries who lived in the first half of the 20th Century – Tsiolkovsky, Goddard, Oberth, Tsander – and who believed that humankind could travel to other planets in the Solar System using new developments in rocket propulsion. These early visionaries established the notion that it was in fact possible to fly to the planets, but their dreams became reality only much later in the second half of the 20th Century after the intervention of World War II created the technological catalyst for accomplishing deep space propulsion. Now, at the end of the 20th Century, humans have set foot on the Moon and sent robotic spacecraft to all the planets except Pluto, including flights to comets and asteroids.

Most of the history of space exploration in the 20th Century is characterized by intense competition for dominance between the USSR and USA. Europe and Japan

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were preoccupied with rebuilding their nations at the dawn of the space age (circa 1950), after the devastation of World War II, while the USSR and USA were developing their ICBMs. The USSR launched the first artificial satellite, Sputnik, on October 4, 1957, using a slightly modified version of their first operational ICBM. The first human space flight was also Soviet; Yuri Gagarin's orbital flight in April 1961. These events shocked Americans, who had difficulty imagining how they could not have been first in space. The Americans also recognized immediately the implications of these events for their national defense. The USA mobilized a massive space development program of its own in 1958, and in 1961 President Kennedy formulated a national goal to send astronauts to the Moon and back before the end of the decade, implicitly meaning that the first human on the Moon should be American, not Soviet.

The Soviet Union responded to this clear and open challenge and initiated a competing national program to send a cosmonaut to the Moon before the Americans. Chertok (1999a) and Siddiqi (2000) have published detailed descriptions of this dramatic 'Race to the Moon'. The Americans won the 'race' on July 20, 1969, with Apollo 11's touchdown on the Moon. The Soviet lunar cosmonaut program never got off the ground after several failures of the N1 heavy lift rocket, the USSR's equivalent to the American Saturn V, after which the USSR turned to robotic spacecraft for exploration of the Moon with very dramatic results. The USSR conducted highly successful robotic lunar rover and sample return missions through 1976, while the Americans shut down their Apollo lunar program in 1972 after six successful flights to the lunar surface.

The 'Space Race' was a Cold War phenomenon, but just like the international air races in the first half of the 20th Century, the space race in the second half of the 20th Century resulted in an explosion of research and technological development. While competition in space exploration between the USSR and the USA originally focused principally on flying humans to the Moon, both countries also competed in sending robotic spacecraft to the Moon and beyond, resulting in enormous scientific progress in understanding our Solar System. It is highly unlikely that the large national investments required for this progress would have been made if it had not been for the political imperatives of the Cold War.

2. From Amateur Rocketry to Missiles and Spacecraft

During the 1930s several groups of amateur rocketry pioneers were established in the USSR, USA, Germany, as well as in other countries. Progress was slow and resources very limited. At that time no government was interested in supporting a program to develop peaceful exploration of space. Military applications were the only hope for obtaining state budgetary support, and this happened first and most successfully in Germany during World War II. When the war ended, the USSR and USA took full advantage of captured German expertise, and began serious development of rocketry for military purposes. As the Cold War developed, each country applied huge resources towards the creation of intercontinental ballistic missiles (ICBMs) capable of delivering nuclear bombs to any point on the Earth.

The enabling technological step towards lunar and planetary space flight was the development of the military ICBM. From the ICBM, it is only a small incremental step to the development of a rocket capable of launching Earth-orbiting satellites, and then only a second small step to a rocket capable of sending spacecraft on trajectories to the Moon and beyond. The developers of ICBMs in both the US and USSR dreamed about space flight from the very beginning, and had always in the back of their minds that the military weapons on which they were working could ultimately be used for space exploration. This was true for Wernher von Braun both in wartime Germany and in the post-war US, and for Sergei Korolev in the Soviet Union. Each of these two key figures rapidly adapted their ICBM rockets for flights to Earth orbit and beyond. The Sputnik launch, and the first Soviet launches to the Moon, were carried out during the initial months of testing the venerable R7 rocket, the Soviet Union's first ICBM launcher. Subsequently, various versions of the R7 became standard launchers for both military and civilian Soviet space programs. At the same time in the USA, early versions of the Atlas ICBM, equipped with various upper stages, was used for early American launch attempts to the Moon and planets.

US rockets were considerably smaller with much less 'throw weight' than their Soviet counterparts. This was the direct result of the military requirement to launch nuclear warheads over inter-continental distances. US warheads were proportionally smaller and lighter than Soviet warheads. The US also used a larger number of vehicle types than the USSR to launch its lunar and planetary probes. This was the result of competition between the US military services to develop their own rockets in the 1950s. The Army, Navy and Air Force all fought to maintain their own rocket programs, which led to a large number of rockets developed by a set of competing manufacturers before consolidation under the Air Force.

In its first two years of its existence in 1958–1959, NASA worked with the Air Force in the early development of lunar mission launch services. For most of the rest of its history, NASA procured its launch services directly from the aerospace manufacturers, often in coordination with the Air Force. The early workhorse launchers for lunar and planetary missions were the Atlas and Titan boosters with various upper stage configurations. In the 1990s with the advent of lower mass spacecraft, the smaller Delta 2 became the launch vehicle of choice. In the Soviet Union, the Ministry of General Engineering managed the design bureaus and manufacturing plants. The Ministry of Defense provided launch facilities for lunar and planetary missions at Baikonur in Kazakstan.

2.1. SOVIET LAUNCH VEHICLES

The R7E launcher also designated 8K72 and known as 'Luna' or Vostok-E was the first 3-stage version of the R-7 rocket. It was an interim modification used exclusively for the first robotic probes to any Solar System destination, the early Luna missions. It was essentially the same as the 2-stage R7 used for launching Sputnik with a 'Block E' propulsion module added to provide Earth escape velocity for the small early Luna spacecraft. The R7E was used to launch Lunas 1–3 in 1959.

The R7M launcher also designated 8K78 in Russia and SL-6/A-2-e in the US and known as 'Molniya', is a 4-stage version of the R-7 rocket using a 'Block I' for the 3^{rd} stage and a restartable 'Block L' for the 4th stage. This vehicle was developed for deep space missions using spacecraft in the 1-ton class and became the workhorse for lunar and planetary missions in the 1960s and early 1970s. It is still in use today. A variant of this vehicle was developed for the Luna soft landing missions in which the avionics were removed from the 3rd and 4th stages to save mass and the spacecraft avionics controlled the functioning of the upper stages. This latter version has the designations 8K78/Ye-6 and 8K78M. The R7M was used to launch Mars 1, Lunas 4–14, Zonds 1–3 and Veneras 1–8.

The U-500K launcher, designated SL-12/D-1-e in the US, is a version of the Proton-K booster using a restartable 'Block D' for a 4th stage (designated 'Proton-D' in this paper). This vehicle was developed for deep space missions using spacecraft in the multi-ton class and became the workhorse for lunar and planetary missions in the 1970s continuing through the 1990s. The U-500K was used to launch Lunas 15–24, Zonds 4–8, Mars 2–7, Venera 9–16, Vegas 1–2, Phobos 1–2 and Mars 96.

The N1 launcher was the Soviet equivalent to the Saturn 5 rocket and was developed to launch spacecraft to carry lunar cosmonauts to the surface of the Moon. It had test flights in February and July of 1969, the latter a spectacular explosion at liftoff that dashed Soviet hopes to compete with the American Apollo program. The N1 had another test flight in 1971 and a final test in 1972. The launcher failed each time and was abandoned. It carried unpiloted versions of lunar spacecraft for testing at the Moon on the launch attempts in 1969 and 1972.

2.2. US LAUNCH VEHICLES

The Air Force Thor-Able rocket consisted of the Thor intermediate range ballistic missile with an 'Able' upper stage. Thor-Able was used to launch Pioneers 1–2.

The Army Juno 2 was a modified version of the Jupiter-C used to launch the first US satellite Explorer 1. Juno 2 was used to launch Pioneers 3–4.

The Atlas series of launch vehicles served as the backbone for US lunar and planetary missions except for the heaviest of spacecraft, which were launched on the Titan series.

The Atlas ICBM booster was augmented with a series of upper stages with increasing capabilities for launching satellites and interplanetary probes. The first was the Atlas-Able used by NASA with Air Force assistance in attempts to launch very small lunar orbiters in 1959–1960, all of which failed. The second vehicle to be developed had a larger Agena upper stage. The Atlas-Agena B was used to launch Lunar Rangers 1–9 and the Mariner 2 mission to Venus. The more capable Atlas-Agena D version was used to launch Lunar Orbiters 1–5 and Mariners 3–5. And finally, the Atlas-Centaur with a cryogenic upper stage was used to launch Lunar Surveyors 1-7, Mariners 6–10 and Pioneers 10–13. The Atlas-Centaur remains in the US inventory today.

The largest expendable booster in the US inventory is the Titan. The Titan 3 and 4 series consist of the Titan 2 ICBM core vehicle augmented with two large solid rocket strap-ons and various upper stages. The Titan 3E with the Centaur upper stage was used to launch the Viking and Voyager spacecraft. The Titan 3C was used to launch Mars Observer, and the Titan 4B with Centaur upper stage was used to launch Cassini-Huygens. A converted military Titan 2G was used by the Department of Defense to launch the Clementine mission jointly developed by DoD and NASA.

Human-rated launchers were also used for lunar and planetary missions. The piloted Apollo missions to the Moon were all launched on the Saturn V. Two spacecraft, Magellan and Galileo, were carried into low Earth orbit using the US Space Shuttle. Each was attached to a 2-stage solid motor upper stage (IUS) for powering the spacecraft to interplanetary trajectory. Magellan and Galileo were developed in the 1980s when NASA had initiated a policy that all spacecraft must be launched by Shuttle, eliminating expendable launch services, a policy discarded after the Challenger disaster but too late for a change to these two missions.

Later in the 1990s with the advent of smaller, lower cost spacecraft with tailored mission objectives, it became possible to use smaller launch vehicles at far less cost. The Delta 2 commercial launcher, with the best reliability record in the US inventory, could now be used for planetary missions and was used to launch NEAR, Stardust, Mars Pathfinder, Mars Global Surveyor, Mars Climate Orbiter and Mars Polar Lander. The Lunar Prospector spacecraft was launched on the smallest launcher ever to be used for a planetary mission, the Athena 2.

A general comparison of Soviet and American lunar and planetary launch vehicles is presented in Figures 1 and 2.

2.3. European launch vehicles

The Ariane was the first European launch vehicle developed using all-European technology. The initial version of this vehicle, the Ariane 1, was used to launch the European Space Agency's (ESA) first planetary mission, Giotto. The second European planetary mission, Huygens, was launched attached to the US Cassini spacecraft on board its Titan 4B Centaur.

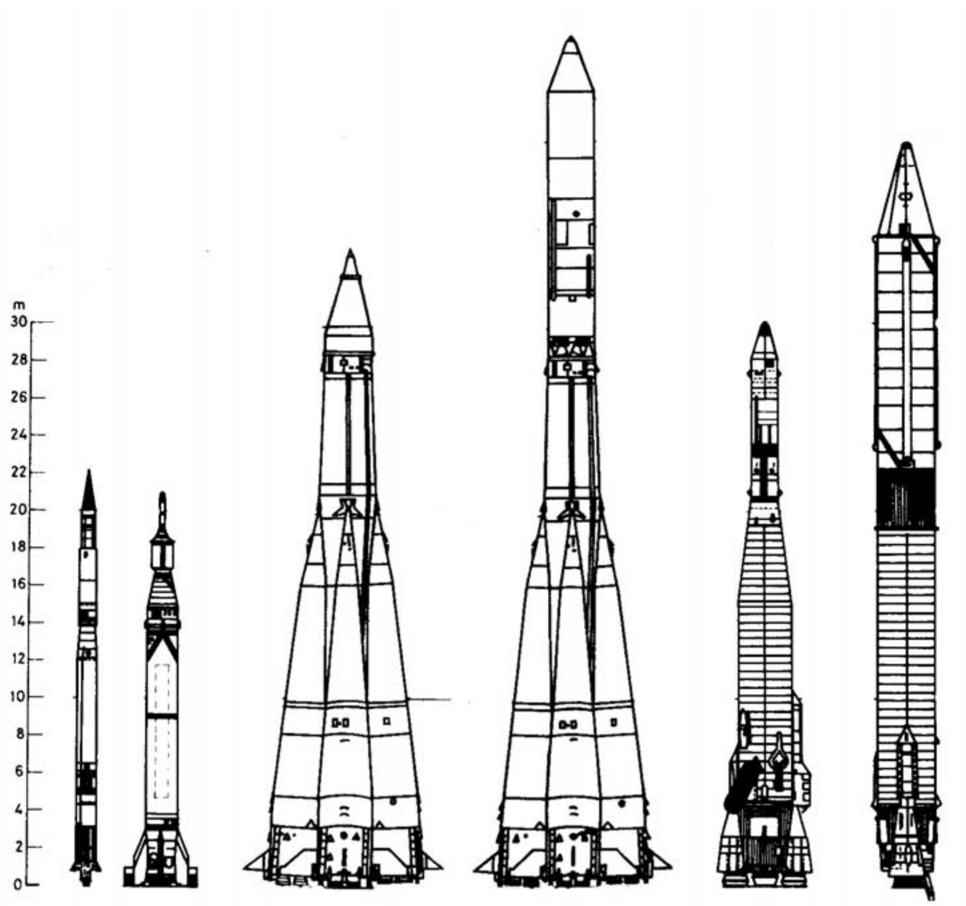

Figure 1. Early Soviet and American launch vehicles. From left to right: US Vanguard and US Jupiter-C used to launch the first US satellites, the USSR R7 used to launch Sputnik-1, the USSR R7 Molniya lunar and planetary launch vehicle, and the US Atlas-Agena D and Atlas-Centaur B lunar and planetary launch vehicles.

2.4. Japanese launch vehicles

Japan is unique in having a separate agency for its science missions, ISAS. ISAS develops its own launchers independent of the Japanese national space agency, NASDA. The ISAS second-generation satellite launcher, M3S2, was used to launch their first planetary spacecraft to Comet Halley and Hiten/Hagoromo to the Moon. The most recent third-generation M5 was used to launch the Nozomi spacecraft to Mars.

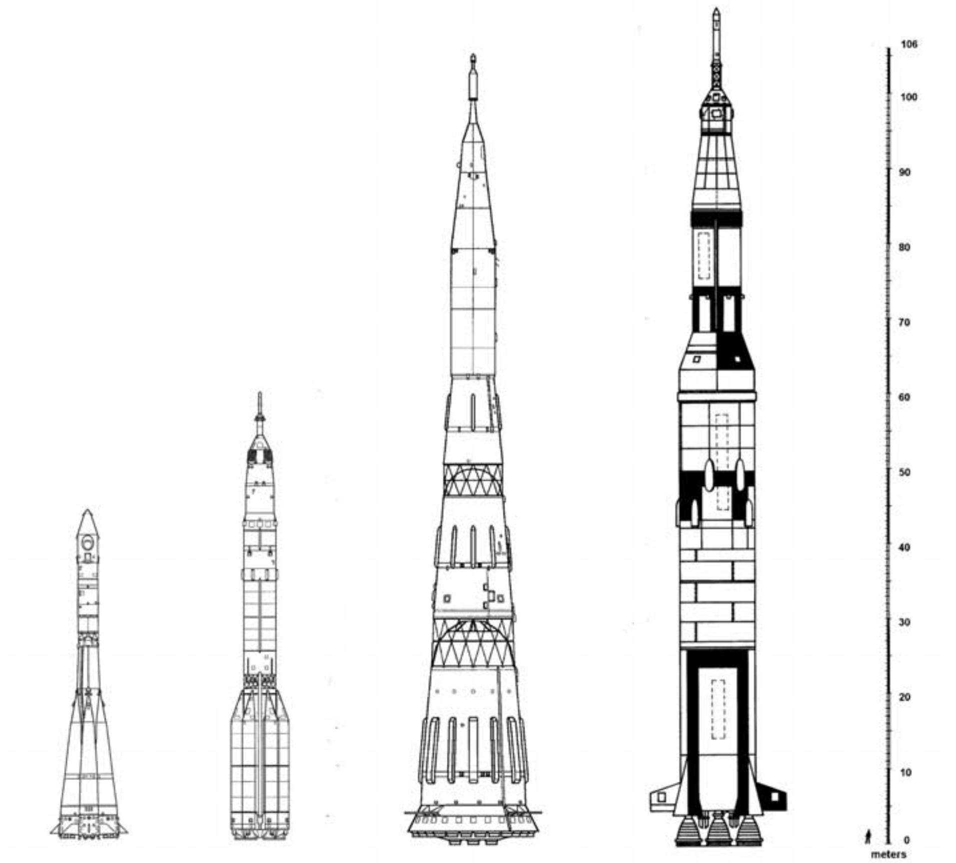

Figure 2. Principal Soviet lunar and planetary launch vehicles compared to the US Saturn V. From left to right: Molniya, Proton-D, N-1, and Saturn V.

3. People and Institutions

In the USSR, military and civilian applications of rocketry were carried out under a veil of great secrecy. Chief Designer S. P. Korolev (1907–1966) and his design bureau led the development of both military and peaceful applications of rocketry. Korolev was known outside a closely guarded inner circle only as ‘Chief Designer’, and his identity was a state secret until his death. Almost nothing was known of the people, institutions and program planning in the Soviet space program. Only after a successful launch was any information released by the USSR. It was not until after the demise of the USSR in 1991 that much of the withheld information became available and those participants who were still alive able to write openly about the dramatic history of the Soviet space program (Chertok, 1999a–d; Semenov, 1996).

In the USA the situation was quite different (Von Braun and Ordway, 1969). Civilian and military space activities were separated. The civilian program was conducted openly in the public eye. A civilian space agency was created that procured its launchers from industries building the same rockets for military purposes. The counterpart to Korolev in the USSR was Wernher von Braun in the USA. An important difference was that von Braun was not hidden from the public, and in fact served as a very public communicator on the American civilian space program. Beginning in the 1950s he thrilled the American public with visions of rocket flight, space stations and flights to Mars in magazines and on television. He designed some of America's first rockets including the one that placed the first US satellite into orbit. He also designed the giant Saturn 5 moon rocket that powered US astronauts to the Moon. Early in the US space program he began concentrating on human space flight and he is now remembered as the 'Chief Designer' of the US Apollo program.

A very important event in the USA was the establishment of NASA in 1958 with an administrative Headquarters in Washington, DC, and several powerful implementing space centers distributed about the country. NASA is wholly responsible for carrying out the nation's civilian space exploration program, including science and technology development, and provides government funding to support the entire enterprise. One space center, the Jet Propulsion Laboratory (JPL) was established to lead in robotic exploration of the Moon and planets, and another, the Manned Spaceflight Center later renamed the Johnson Spaceflight Center (JSC), was established to lead in human exploration of space. Dr. William Pickering was the Director of JPL and a leading figure in rocket development for the US Army. JPL was a Division of the California Institute of Technology and had been conducting research in rocketry since the 1930s first under the leadership of Theodore von Karman and followed by Frank Malina and William Pickering. JSC was a new center, and Dr. Robert Gilruth was appointed its first Director.

In the USA, laboratories in space centers and universities prepared scientific experiments for planetary missions. In the USSR, Institutes of the Academy of Science generally filled this role. In the early years, the leading institute was the Institute of Geochemistry and Analytical Chemistry (GEOKHI) also known as the Vernadsky Institute. In the early 1970s, the newly established (in 1965) Space Research Institute began to play an important role.

The USSR never had a space agency like NASA. Strategy was under the nominal responsibility of MNTS (Mezhduvedomstvennyi Nauchno-Tekhnicheckii Soviet, or Inter-Department Scientific and Technical Council) headed by M.V. Keldysh (1911–1978), but there was a managing body at the highest level of the Central Committee of the Communist Party, VPK (Voenno-Promyshlennaya Komissiya, or Commission for Military Industry). In reality, the personal preferences and intentions of Main Designers such as S. P. Korolev and G. N. Babakin were most influential for planning, especially during the early years. The Ministry of General Engineering provided technical coordination and governmental budgetary support enormous in scale.

From the outset until 1965 the leading industrial organization in the USSR responsible for lunar and planetary spacecraft was the OKB-1 (Osoboe Konstruktorskoe Byuro No. 1 or Special Design Bureau No. 1) managed by Chief Designer S. P. Korolev. OKB-1 designed, developed, tested, and operated spacecraft in flight, and also carried out a very extensive program of piloted missions. It became increasingly difficult to maintain responsibility for all these diverse programs, and in 1965 all robotic lunar and planetary projects were transferred to another industrial facility: the S. A. Lavochkin Design Bureau and Plant. This Design Bureau was managed by Main Designer G.N. Babakin (1914–1971). The Lavochkin Design Bureau had a tradition and a culture of high quality aviation manufacture. OKB-1 retained responsibility for the program to develop piloted flights to the Moon (Zond and N1 missions listed in Table I), a program which ultimately failed. Later in 1974 the 'Lavochkin Facility' was re-named Nauchno-Proizvodstvennoe Obyedinenie imeni S.A.Lavochkina (NPOL) , or the S. A. Lavochkin Scientific Industrial Association – unofficially the Lavochkin Association. For simplicity, the designation 'NPOL' will be used for all periods of its history. A history of NPOL has been published recently (Serebrennikov *et al.*, 1997).

The European space program began with the establishment of the European Space Research Organization (ESRO) in 1962 with ten founding members from the largest Western European countries. After having developed Europe's rocket technology to maturity, this organization became the European Space Agency (ESA) in 1975 with a total of 15 Western European nations and Canada as a cooperating state. ESA's headquarters are in Paris, France, and its implementing center for overseeing the development of deep space flight missions is the European Space Research and Technology Center (ESTEC) in Noordwijk, Netherlands. The Ariane rocket was the key ESA product that provided European access to deep space, and in the next 25 years ESA raised the status of European space exploration to a competitive and cooperating partner with the US and Russia. ESA made a commanding entrance into planetary exploration in 1986 with its Giotto mission to Comet Halley.

Japan established its own space science institution in 1964, the Institute of Space and Aeronautical Science (ISAS). The National Space Development Agency (NASDA) devoted to space applications was established later in 1969. In 1981, ISAS was reorganized and its position in the government hierarchy was strengthened. Shortly thereafter, ISAS launched its first deep space missions to Comet Halley. Japan is unique in having a separate academic-style government agency for conducting space science missions, a situation destined to change by its merger with NASDA in coming years.

4. Missions to the Moon

4.1. The Early Years: 1959–1965

Table I lists events in lunar exploration chronologically. Less than one year after Sputnik 1, both the USA and the USSR attempted to launch spacecraft to the Moon in August and September 1958. These first launch attempts failed when the rockets were destroyed soon after launch. Later in 1958 the US launched three Pioneer spacecraft towards the Moon but each failed to reach escape velocity. Two more launch attempts from Baikonur also failed, again due to destruction of the launch vehicles. The USSR won this early race to the Moon in January 1959 when Luna 1 achieved distinction as the first successful flyby of the Moon, even though the spacecraft was intended to impact the surface. In September 1959, Luna 2 achieved complete success as the first spacecraft to impact the Moon. Figure 3 illustrates the generations of Soviet lunar spacecraft from Luna-1 to the lunar sample return landers.

After the successful flight of Luna 2, the USSR switched mission objectives from impact flights to flyby investigations and was rewarded on their first attempt in October 1959 when Luna 3 transmitted the first images of the far side of the Moon. Two more attempts in April 1960 with a new spacecraft failed due to problems with the launch vehicle. The USSR then stood down from further attempts on the Moon for almost three years while they turned their attention to Venus and Mars and to development of a new generation of lunar and planetary spacecraft.

While the USSR pursued its three successful lunar flights in 1959, a fourth attempt at a lunar flyby by the US failed in March 1959 when the launch vehicle once again did not provide sufficient velocity and the Pioneer 4 spacecraft flew past the Moon at a very large distance. Four subsequent attempts in 1959 and 1960 to send a small orbiter to the Moon failed due to problems with the launch vehicles. Four more years were to pass with six more failures before the first fully successful American mission to Moon.

These early attempts at flights to the Moon were as much tests of the launch vehicle and new upper stages as they were scientific expeditions. While certainly frustrating, the high failure rate was not totally unexpected in the early days of development of complex technology for interplanetary rockets and spacecraft. In the first eight years of lunar and planetary exploration from 1958 through 1965, there were 52 failures out of 61 launch attempts to the Moon, Mars and Venus. Launch vehicle problems accounted for 38 of the 52 failures, the remaining 14 due to spacecraft in-flight failures. Two of the 9 successful missions only partially met their goals. The proportion of launch vehicle failures dropped as time went on throughout the 1960s, particularly in the US after 1965 where more attention was given to ground testing.

The first 21 Soviet lunar mission attempts were conducted by OKB-1. After the early success with Lunas 1–3 in 1959, luck turned against the USSR. The

TABLE I

Missions to the Moon in the 20th century

Mission	Type	Country	Launch date	Launch vehicle
1958				
Pioneer 0	orbiter	USA	17 Aug 1958	Thor-Able
ARPA-Air Force mission Thor-Able 1[1]. Spacecraft carried a camera, magnetometer and micrometeoroid detector. Booster exploded at 77 s.				
[Luna] E-1 No. 1	impactor	USSR	23 Sept 1958	Vostok-E
First OKB-1 mission to the solar system[2]. Stack was destroyed in flight at the end of the first stage burn. Spacecraft carried USSR pennant and instruments to detect ions, cosmic rays, magnetic fields and micrometeoroids (Chertok, 1999c).				
Pioneer 1	orbiter	USA	11 Oct 1958	Thor-Able
ARPA-Air Force mission[1]. Payload augmented with a Van Allen ion chamber. Second stage shut down early due to a guidance error. Reached 115 000 km before falling back to earth. Returned data on the Van Allen Radiation Belts.				
[Luna] E-1 No. 2	impactor	USSR	12 Oct 1958	Vostok-E
Launch failure identical to E-1 No. 1. Spacecraft carried scientific instruments and USSR pennant (Chertok, 1999c).				
Pioneer 2	orbiter	USA	8 Nov 1958	Thor-Able
ARPA-Air Force mission[1]. Pioneer 1 payload augmented again with a proportional counter. Third stage failed to ignite. Reached 1550 km before falling back to earth. No useful data.				
[Luna] E-1 No. 3	impactor	USSR	4 Dec 1958	Vostok-E
Second stage core engine shut down prematurely after 4 min. Spacecraft carried scientific instruments and USSR pennant (Chertok, 1999c).				
Pioneer 3	flyby	USA	6 Dec 1958	Juno-2
ARPA-Army mission[1]. Spacecraft carried two Geiger-Muller tubes, but no camera. First stage shut down prematurely. Reached 107 500 km before falling back to earth. Returned data on the Van Allen Radiation Belts.				
1959				
Luna 1	impactor	USSR	2 Jan 1959	Vostok-E
Lunar impact attempt missed the Moon by 6000 km on 4 Jan. Spacecraft carried USSR pennant and instruments to detect ions, cosmic rays, magnetic fields and micrometeoroids. Released a sodium cloud visible from the ground (‘Artificial Comet’). Luna 1 was the first spacecraft to escape Earth gravity, first lunar flyby, first to enter solar orbit, and first *in situ* measurement of the solar wind (Chertok, 1999c).				
Pioneer 4	flyby	USA	3 Mar 1959	Juno-2
ARPA-Army mission[1]. Nearly identical spacecraft to Pioneer 3. Launched with a lower injection velocity than planned and flew past the Moon at 60 000 km distance on 4 Mar. Tracked to 650 000 km, measured cosmic radiation. Entered solar orbit.				
[Luna] E-1A No. 5	impactor	USSR	18 Jun 1959	Vostok-E
Second stage destroyed in the 3rd minute of flight after inertial guidance failed. Spacecraft carried scientific instruments and USSR pennant (Chertok, 1999c).				
Luna 2	impactor	USSR	12 Sep 1959	Vostok-E
First successful lunar impactor and first spacecraft to impact another celestial body. Impacted the Moon on 14 Sept 1959 at 23:02:23 UT in Palus Putredinis. Carried scientific instruments and USSR pennant, found the moon to have virtually no magnetic field (Chertok, 1999c).				

TABLE I

Continued

[Pioneer] Atlas-Able 4	orbiter	USA	24 Sep 1959	Atlas-Able
First NASA lunar mission, but done in cooperation with the Air Force. Pad explosion during static tests; intended for launch in Oct.				
Luna 3	circumlunar	USSR	4 Oct 1959	Vostok-E
'Automatic Interplanetary Station'. Circled the Moon on 7 Oct and successfully transmitted the first images of the far side of the Moon. Photographed 70% of the backside hemisphere in 17 frames (Semenov, 1996; Annon., 1959; Annon., 1960).				
[Pioneer] P-3	orbiter	USA	26 Nov 1959	Atlas-Able
Shroud broke away at 45 s, destroying the spacecraft.				
1960				
[Luna] E-3 No. 1	circumlunar	USSR	15 Apr 1960	Vostok-E
Third stage malfunction. Intended for imaging the lunar far side (Semenov, 1996; Chertok, 1999).				
[Luna] E-3 No. 2	circumlunar	USSR	19 Apr 1960	Vostok-E
First stage disintegrated at liftoff. Intended for imaging the lunar far side (Chertok, 1999d).				
[Pioneer] P-30	orbiter	USA	25 Sep 1960	Atlas-Able
Pioneer-class NASA mission. Launch failed; second stage malfunctioned.				
[Pioneer] P-31	orbiter	USA	15 Dec 1960	Atlas-Able
Pioneer-class NASA mission. Launch failed; vehicle exploded at 70 s.				
1961				
Ranger 1	deep space test	USA	23 Aug 1961	Atlas-Agena B
Block I Rangers targeted for large elliptical Earth orbit beyond the Moon. Carried space physics payload with no lunar objectives. Entered earth orbit after Agena upper-stage failed to ignite for its second burn. Reentered on 30 Aug. (Hall, 1977).				
Ranger 2	deep space test	USA	18 Nov 1961	Atlas-Agena B
Entered earth orbit after Agena upper-stage failed. Reentered on 19 Nov. (Hall, 1977).				
1962				
Ranger 3	hard lander	USA	26 Jan 1962	Atlas-Agena B
Block II Ranger objectives were lunar photography from descent with a separated hard lander seismometer. Excessive velocity imparted by launch vehicle prohibited lunar impact. Spacecraft computer malfunctioned during a terminal maneuver in an attempt to photograph the Moon during flyby. The tumbling spacecraft passed the Moon at a distance of 37 745 km on Jan 28 (Hall, 1977).				
Ranger 4	hard lander	USA	23 Apr 1962	Atlas-Agena B
Spacecraft computer and sequencer failed in Earth orbit. Impacted the lunar far side on April 26 (Hall, 1977).				
Ranger 5	hard lander	USA	18 Oct 1962	Atlas-Agena B
Spacecraft power and control system malfunctioned in Earth orbit. Passed by the Moon at 724 km distance on Oct 21 (Hall, 1977).				

TABLE I
Continued

1963

[Luna] E-6 No. 2 lander USSR 4 Jan 1963 Molniya

Luna class probe. Fourth stage failed to start, left in Earth orbit (Chertok, 1999d). USA lists as Sputnik 33.

[Luna] E-6 No. 3 lander USSR 3 Feb 1963 Molniya

Luna class probe. Did not reach Earth orbit due to improper pitch angle setting beginning at 105.5 s (Chertok, 1999d).

Luna 4 lander USSR 2 April 1963 Molniya

Spacecraft navigation system malfunctioned enroute, missed the Moon by 8500 km on 5 Apr. (Chertok, 1999d).

1964

Ranger 6 impactor USA 30 Jan 1964 Atlas-Agena B

First Block III Ranger. Impacted the Sea of Tranquility on Feb 2. Spacecraft operated perfectly, but the cameras failed to operate (Hall, 1977).

[Luna] E-6 No. 6 lander USSR 21 Mar 1964 Molniya

Luna class probe. Third stage engine failure, did not reach Earth orbit (Chertok, 1999d).

[Luna] E-6 No. 5 lander USSR 20 Apr 1964 Molniya

Luna class probe. Power was not transferred from the 3rd to 4th stage. Did not reach earth orbit (Chertok, 1999d).

Ranger 7 impactor USA 28 Jul 1964 Atlas-Agena B

First completely successful US lunar mission. Transmitted 4316 photos of the Moon before impact in the Sea of Clouds at 11S 21W on July 31 (Hall, 1977).

1965

Ranger 8 impactor USA 17 Feb 1965 Atlas-Agena B

Transmitted 7137 photos of the Sea of Tranquility before impact on Feb 20 (Hall, 1977).

[Luna] Cosmos 60 lander USSR 12 Mar 1965 Molniya

Luna class probe. Fourth stage failed to ignite, left in Earth orbit (Chertok, 1999d).

Ranger 9 impactor USA 21 Mar 1965 Atlas-Agena B

Transmitted 5814 photos before impact inside Alphonsus Crater on Mar 24 (Hall, 1977).

[Luna] E-6 No. 8 lander USSR 10 Apr 1965 Molniya

Luna class probe. Third stage engine failure. Did not reach earth orbit (Chertok, 1999d).

Luna 5 lander USSR 9 May 1965 Molniya

Major errors in navigation and control system due to thermal problems. Retrorockets malfunctioned, crashed into the Sea of Clouds on 12 May (Chertok, 1999d).

Luna 6 lander USSR 8 Jun 1965 Molniya

Mid-course maneuver failed due to command error. Spacecraft missed the Moon by 160 000 km on 11 Jun. (Chertok, 1999d).

Zond 3 flyby USSR 18 Jul 1965 Molniya

Flew past the Moon at 9220 km on 20 Jul. Returned 25 photos of the lunar farside. Test mission for a Mars spacecraft and launcher since Mars was not in proper position for encounter. Spacecraft failed after 7.5 months before reaching Mars distance (Chertok, 1999d).

TABLE I

Continued

Luna 7	lander	USSR	4 Oct 1965	Molniya

First launch attempt on 4 Sep 1965 was cancelled and the rocket removed from the launch stand for major repairs to the control system. The second launch attempt succeeded on 4 Oct 1965. Attitude control system failed during lunar braking maneuver leading to excessive speed. Crashed into the Ocean of Storms near the Crater Kepler on 7 Oct (Chertok, 1999d).

Luna 8	lander	USSR	3 Dec 1965	Molniya

Attitude control system failed just prior to landing resulting in a short engine firing. Crashed into the Ocean of Storms near Crater Galilaei on 7 Dec. (Chertok, 1999d).

1966

Luna 9	lander	USSR	31 Jan 1966	Molniya

First successful lunar lander and first lander on another planetary body. Landed on the Moon 3 Feb 1966 at 18:44:54 UT, at 7.08N 295.63E in Oceanus Procellarum. Returned the first pictures from the lunar surface. First lunar mission under NPOL responsibility[4] (Annon., 1966).

[Luna] Cosmos 111	orbiter	USSR	1 Mar 1966	Molniya

Luna class lander modified for an orbiter. Trans-lunar injection failed, left in Earth orbit.

Luna 10	orbiter	USSR	31 Mar 1966	Molniya

Luna class lander modified for a lunar orbiter. Became the first successful lunar orbiter on 3 Apr and first orbiter of another celestial body. Achieved 350 by 1000 km orbit at 71.9° inclination. Lasted 56 days studying lunar surface radiation, magnetic and gravity fields.

Surveyor 1	lander	USA	30 May 1966	Atlas-Centaur

First US lunar lander. Landed in the Ocean of Storms on 2 Jun 1966, 06:17:37 UT, at 2.45S 316.79E. Transmitted 11 237 photographs of the surface.

Lunar Orbiter 1	orbiter	USA	10 Aug 1966	Atlas-Agena D

First US lunar orbiter on 14 Aug. Photographic mapper for Apollo; examined 9 landing sites. Took first photo of the Earth from lunar distance. Commanded impact on far side 29 Oct.

Luna 11	orbiter	USSR	24 Aug 1966	Molniya

Luna class spacecraft modified for orbital lunar photography and plasma science. Entered 159 by 1193 km orbit on 28 Aug. Stabilization problem prevented useful images. Ceased on 1 Oct after 38 days.

Surveyor 2	lander	USA	20 Sep 1966	Atlas-Centaur

Crashed southeast of Crater Copernicus on 22 Sep. One of three vernier engines failed to ignite during the midcourse maneuver.

Luna 12	orbiter	USSR	22 Oct 1966	Molniya

Luna class spacecraft modified for orbital lunar photography and plasma science. Entered orbit on 25 Oct. Transmitted pictures of the Sea of Rains and Crater Aristarchus. Tested electric motors for a lunar rover. Active for 85 days.

Lunar Orbiter 2	orbiter	USA	6 Nov 1966	Atlas-Agena D

Orbited on 9 Nov. Photographic mapper for Apollo. Returned 422 pictures including Ranger 8 impact site and debris. Commanded impact on 11 Oct 1967.

Luna 13	lander	USSR	21 Dec 1966	Molniya

Second soft lander with more extensive lander science. Landed 24 Dec 1966 at 18:01:00 UT, 18.87N 297.95E in Oceanus Procellarum. Returned pictures from the surface and extended two arms to measure soil density and surface radioactivity.

TABLE I
Continued

Lunar Orbiter 3	orbiter	USA	5 Feb 1967	Atlas-Agena D
Orbited on 8 Feb. Photographic mapper for Apollo. Returned 307 photos including picture of Surveyor 1 on the surface. Provided gravitational field and lunar environmental data. Commanded impact on 9 Oct.				
1967				
Surveyor 3	lander	USA	17 Apr 1967	Atlas-Centaur
Vernier engines did not shut down immediately and s/c bounced twice before landing on 20 Apr, 00:04:53 UT, at 2.94S 336.66E 230 miles south of Crater Copernicus in the Ocean of Storms. Transmitted 6315 photos including a picture of Earth during lunar eclipse. Used a scoop to make first excavation and bearing test on lunar soil.				
Lunar Orbiter 4	orbiter	USA	4 May 1967	Atlas-Agena D
Orbited at a polar inclination on 8 May. Returned 326 photos including first of the lunar south pole. Commanded impact on 6 Oct.				
[Luna] Cosmos 159	orbiter	USSR	16 May 1967	Molniya
Second modification of the luna class orbiter; for precise determination of lunar gravity field and to test deep space communications for later human flights. Planned for test of navigational capabilities in high earth orbit, the fourth stage burn terminated early resulting in a lower apogee than desired.				
Surveyor 4	lander	USA	14 Jul 1967	Atlas-Centaur
Lost contact with Earth 2.5 min before touchdown on 17 Jul in Sinus Medii. Possible retroengine explosion.				
Lunar Orbiter 5	orbiter	USA	1 Aug 1967	Atlas-Agena D
Entered polar orbit on 5 Aug. Increased lunar photo coverage to better than 99%. Returned micrometeroid data and 212 photo frames including 5 landing sites. Commanded impact on 31 Jan 1968.				
Surveyor 5	lander	USA	8 Sept 1967	Atlas-Centaur
Landed 11 Sep, 01:01:06 UT, in the Sea of Tranquility at 1.41N 23.18E 15.5 miles from the future Apollo 11 landing site. First in-situ elemental chemical soil analysis (alpha-scatter). Returned data on surface radar and thermal reflectivity as well as more than 19 000 photos.				
[Zond] 7K-L1 No. 4L	circumlunar/return	USSR	27 Sept 1967	Proton-D
Unpiloted test of Soyuz lunar craft. Booster failure, 1 of 6 engines failed to ignite (Chertok, 1999a).				
Surveyor 6	lander	USA	7 Nov 1967	Atlas-Centaur
Landed 10 Nov, 01:01:06 UT, at 0.46N 358.63E in Sinus Medii. On 17 Nov the lander's engines were used to hop the lander 10 ft. high and 8 ft. to the west for stereoscopic measurements. Sent back 30 065 pictures.				
[Zond] 7K-L1 No. 5L	circumlunar/return	USSR	22 Nov 1967	Proton-D
Unpiloted test of Soyuz lunar craft. Second stage failure, 1 of 4 engines failed to ignite (Chertok, 1999a).				
1968				
Surveyor 7	lander	USA	7 Jan 1968	Atlas-Centaur
Landed 10 Jan 1968, 01:05:36 UT, at 41.01S 348.59E, 18 miles north of crater Tycho on a rough ejecta blanket. Dug a trench in the soil and conducted alpha-scattering soil analysis. Returned 21 274 photos.				

TABLE I

Continued

[Luna] E-6LS No. 112	orbiter	USSR	7 Feb 1968	Molniya
Identical to Luna 14. Third stage terminated early at 524 s, ran out of propellant.				
Zond 4	lunar distance/return	USSR	2 Mar 1968	Proton-D
Unpiloted test of Soyuz lunar craft. Test flight at lunar distance. Many system failures occurred in flight. Self-destructed while on parachute descent (Chertok, 1999a).				
Luna 14	orbiter	USSR	7 Apr 1968	Molniya
Entered orbit on 10 Apr. Mapped lunar gravity field with high precision, conducted tests of deep space communications, measured solar wind charged particles and cosmic rays in lunar orbit, and measured the librational motion of the Moon. Same spacecraft as the previous two failed Luna orbiters.				
[Zond] 7K-L1 No. 7L	circumlunar/return	USSR	22 Apr 1968	Proton-D
Unpiloted test of Soyuz lunar craft. Second stage shutdown due to a command error from the spacecraft. Later on 14 Jul, a planned launch of the 7K-L1 No. 8 spacecraft went awry when the 4th stage oxygen tank exploded on the pad (Chertok, 1999a).				
Zond 5	circumlunar/return	USSR	14 Sep 1968	Proton-D
Unpiloted test of Soyuz lunar craft. First successful circumlunar flight and return. Recovered in the Indian Ocean on 21 Sep 1968. Took photos of the Earth and returned a biological package including turtles (Chertok, 1999a).				
Zond 6	circumlunar/return	USSR	10 Nov 1968	Proton-D
Unpiloted test of Soyuz lunar craft. Depressurization failure in transit, the descent system failed on Earth entry 17 Nov, 1968, and the vehicle crashed inside the USSR. Photographs including lunar far side images were recovered (Chertok, 1999d).				
Apollo 8	piloted orbiter	USA	21 Dec 1968	Saturn 5
First human spaceflight to the Moon. Entered orbit on 24 Dec. Left after 10 orbits were completed on 25 Dec and returned to Earth 27 Dec.				
1969				
[Zond] 7K-L1 No. 13L	circumlunar/return	USSR	20 Jan 1969	Proton-D
Unpiloted test of Soyuz lunar craft. Second stage failure (Chertok, 1999a).				
[Luna] E-8 No. 201	lander/rover	USSR	19 Feb 1969	Proton-D
Payload stack disintegrated at t = 51 s with subsequent vehicle explosion. Caused by a shroud failure (Chertok, 1999a).				
[Zond] 7K-L1S No. 3S	orbiter/return	USSR	21 Feb 1969	N1-L3
First test of the N1 launcher. Carried unpiloted test of Zond circumlunar spacecraft modified for lunar orbit. Launch failed when the booster engines shut down at 70 s (Chertok, 1999a).				
Apollo 10	piloted orbiter	USA	18 May 1969	Saturn 5
Entered lunar orbit on 22 May. Piloted lunar lander was tested in lunar orbit. Came within 14.9 km of the lunar surface. Returned 26 May.				
[Luna] E-8-5 No. 402	sample return	USSR	14 Jun 1969	Proton-D
First attempt at sample return. Fourth stage failed to ignite.				
[Zond] 7K-L1S No. 5L	orbiter/return	USSR	3 Jul 1969	N1-L3
Second test of the N1 launcher. Carried unpiloted test of Zond circumlunar spacecraft modified for lunar orbit. Launch failed when the booster exploded spectacularly on liftoff (Chertok, 1999a).				

TABLE I
Continued

Luna 15	sample return	USSR	13 Jul 1969	Proton-D
Attempt to return first lunar samples before Apollo 11. Orbited on 17 Jul. Began descent maneuver on 21 Jul after 52 orbits, but crashed in the Sea of Crises about 800 km east of Apollo 11 surface operations.				
Apollo 11	piloted orbiter/lander	USA	16 Jul 1969	Saturn 5
Orbited on 19 July. First human lunar landing in the Sea of Tranquillity at 00.69N 23.43E on 20 July 1969, 4:18 pm EDT. First footfall on the Moon occurred at 10:56 pm EDT 20 July 1969. Astronauts deployed experiments on the lunar surface, lofted back to orbit and left for Earth on 21 Jul. Astronauts returned to Earth safely on 24 Jul bearing 21.7 kg of lunar rocks and soil.				
Zond 7	circumlunar/return	USSR	7 Aug 1969	Proton-D
Unpiloted test of Soyuz lunar craft. Circumlunar mission returned to Earth on 14 Aug. Returned a biological package and color pictures of the Earth and lunar far side (Chertok, 1999a).				
[Luna] Cosmos 300	sample return	USSR	23 Sep 1969	Proton-D
Fourth stage failed to re-ignite. Reentered 27 Sep.				
[Luna] Cosmos 305	sample return	USSR	22 Oct 1969	Proton-D
Fourth stage misfired. Reentered 24 Oct.				
Apollo 12	piloted orbiter/lander	USA	14 Nov 1969	Saturn 5
Successful precision landing on 19 Nov just 156 meters from Surveyor 3 at 03.20N 23.38W. Set up an Apollo Lunar Surface Experiment Package (ALSEP) experiment package deployed by all subsequent crews. Returned 34.4 kg of lunar material and parts of the Surveyor 3 spacecraft on 24 Nov.				
1970				
[Luna] E-8-5 No. 405	sample return	USSR	6 Feb 1970	Proton-D
Second stage shut down prematurely at 127 s and the vehicle was destroyed.				
Apollo 13	piloted orbiter/lander	USA	11 Apr 1970	Saturn 5
An explosion occurred in the support module enroute, terminating all lunar objectives. Astronauts returned to Earth safely on 17 Apr using the lunar lander as a lifeboat.				
Luna 16	sample return	USSR	12 Sep 1970	Proton-D
First robotic planetary sample return. Landed 20 Sep 1970, 05:18:00 UT, at 00.68S 56.30E in Mare Fecunditatis. An automatic drill rig was deployed, samples collected and 105 g of soil were returned to Earth on 24 Sep (Vinogradov, 1974).				
Zond 8	circumlunar/return	USSR	20 Oct 1970	Proton-D
Unpiloted test of Soyuz lunar craft. Circumlunar mission returned to Earth on 27 Oct 1970. Recovered successfully in the Indian Ocean (Chertok, 1999a).				
Luna 17	lander/rover	USSR	10 Nov 1970	Proton-D
Landed 17 Nov 1970, 03:47:00 UT, at 38.28N 325.00E in Mare Imbrium. Deployed the first planetary rover. Lunokhod 1 traveled over the lunar surface for 11 lunar days (300 terrestrial days) driven by a 5-man team on Earth. Returned over 20 000 photos, and conducted hundred of soil analyses and mechanical tests (Vinogradov, 1971).				

TABLE I
Continued

1971				
Apollo 14	piloted orbiter/lander	USA	31 Jan 1971	Saturn 5
Landed 5 Feb in Fra Mauro at 3.40S 17.28E. Lifted off the Moon on 6 Feb and the astronauts returned to Earth on 9 Feb with 42.9 kg of lunar material.				
Apollo 15	piloted orbiter/lander/rover	USA	26 Jul 1971	Saturn 5
Landed 30 Jul at 26.6N 3.39E in Hadley-Apennines. First piloted lunar rover had a range of several km. The orbiter carried scientific sensors and deployed a 36.3 kg lunar sub-satellite on 4 Aug. Astronauts returned to Earth on 7 Aug with 76.8 kg of lunar material.				
Luna 18	sample return	USSR	2 Sep 1971	Proton-D
Attempted landing after 54 orbits on 11 Sep at 3.5N 56.5E. Communications ceased abruptly near touchdown.				
Luna 19	orbiter	USSR	28 Sep 1971	Proton-D
Successful photographic mapper. Lasted more than 4000 orbits over more than a year. Studied the lunar gravity field and returned photos.				
1972				
Luna 20	sample return	USSR	14 Feb 1972	Proton-D
Landed 21 Feb 1972, 19:19:00 UT, at 3.57N 56.50E in Mare Fecunditatis 1.8 km from the Luna 18 crash site. Sent images from the surface and returned 55 g of lunar highland material to Earth on 25 Feb 1972.				
Apollo 16	piloted orbiter/lander/rover	USA	16 Apr 1972	Saturn 5
Landed 20 Apr at 9.00N 15.31E in the Descarte area with a piloted lunar roving vehicle. The orbiter deployed a 36.3 kg lunar sub-satellite on 19 Apr. Returned with 94.7 kg of lunar material on 27 Apr.				
[Zond] 7K-LOK No. 6A	orbiter/return	USSR	23 Nov 1972	N1-L3
Fourth and final test of the N1 launcher. Carried an unpiloted test of the Soyuz L3 lunar orbital module. Launch failed when the booster exploded near the end of its burn at 107 s. Followed the third launch of the N1 on 28 June, 1971, carrying a mock-up spacecraft, which failed due to loss of roll control and breakup at 48 s. (Chertok, 1999a)				
Apollo 17	piloted orbiter/lander/rover	USA	7 Dec 1972	Saturn 5
Final Apollo mission. Landed at 20.10N 30.46E in Taurus-Littrow on 11 Dec carrying the first and only scientist-astronaut. Included a piloted lunar roving vehicle, which covered 30.5 km in a 75 h stay on the surface. Returned to earth 19 Dec with 110.5 kg of lunar soil and rock.				
1973				
Luna 21	lander/rover	USSR	8 Jan 1973	Proton-D
Landed 15 Jan 1973, 23:35:00 UT, at 25.51N 30.38E in Mare Serenetatis. Deployed rover Lunokhod 2 with improved instrumentation. Ceased operations on the 5th lunar day.				
1974				
Luna 22	orbiter	USSR	29 May 1974	Proton-D
Photographic mapper entered lunar orbit on 2 Jun. Initially placed in circular orbit, then lowered for better resolution images. Carried an altimeter and measured surface composition using gamma-ray spectrometry.				

TABLE I
Continued

Luna 23	sample return	USSR	28 Oct 1974	Proton-D
Landed 6 Nov in the Sea of Crises. Sampling device damaged on landing. Lasted 3 days, no return attempted.				
1975				
[Luna] E-8-5M No. 412	sample return	USSR	16 Oct 1975	Proton-D
Fourth stage failed during its first burn and the spacecraft did not reach earth orbit.				
1976				
Luna 24	sample return	USSR	9 Aug 1976	Proton-D
Entered orbit on 14 Aug and landed 02:00:00 UT 18 Aug at 12.25N 62.20E in Mare Crisium. Carried an improved drill system. Returned 170 g including core samples on 22 Aug. US and British scientists were given samples for analysis.				
1989				
Galileo	flyby	USA	18 Oct 1989	Shuttle-IUS
Conducted two flybys of the Earth/Moon system on the way to Jupiter. Images of the lunar far side transmitted during the first flyby on 8 Dec 1990, and images of the lunar north polar area were transmitted during the second flyby on Dec 8 1992.				
1990				
Hiten	flyby/orbiter	Japan	24 Jan 1990	M3S2
ISAS mission flew by the Moon and deployed the Hagoromo orbiter. No communication from Hagoromo.				
1994				
Clementine	orbiter	USA	25 Jan 1994	Titan 2G
Joint DoD-NASA technology test mission[3]. Official DoD name was 'Deep Space Probe Technology Science Experiment'. Spacecraft left earth orbit on 3 Feb and entered lunar orbit on 19 Feb. Carried four cameras for global imaging with 125–250 m/pixel resolution and other remote measurements. Carried UV/Vis and near-infrared cameras for mineralogical mapping, and a laser altimeter for constructing the first lunar topographic map. Departed lunar orbit on 3 May and on 7 May failed enroute to the near-earth asteroid Geographos due to a software error depleting the attitude control propellant (Clementine, 1994).				
1997				
Cassini	flyby	USA	15 Oct 1997	Titan 4B
Conducted a flyby of the Earth/Moon system on 17 Aug 1999 enroute to Saturn. Lunar images were taken principally for camera calibration purposes.				

TABLE I
Continued

1998				
Lunar Prospector	orbiter	USA	7 Jan 1998	Athena 2
Entered lunar polar orbit 11 Jan. Produced many global maps of geology, topography, mineralogy, magnetic and gravity fields. Found crustal H atoms buried at the surface in both polar regions, presumably due to water ice in the polar crust. Terminated 31 July 1999 by impact in a permanently shadowed crater at the lunar south pole. No water plume was observed from Earth (Lunar Prospector, 1998).				

[1]ARPA was the Advanced Research Project Agency, a research body of US Armed Forces in the 1950's and 60's.
[2]OKB-1 was the Special Design Bureau led by General Designer S. P. Korolev (1907–1966). This facility was the main organization in the USSR responsible for design, manufacture and flight control of all Luna, Venera, and Mars missions until 1966, and all Zond missions (Chertok, 1999c). This facility passed through several re-organizations and name modifications after 1965 and is now called the 'Energiya Corporation'.
[3]All later missions to Moon were NASA projects except Clementine in 1994, which was a joint NASA-DoD (Department of Defense) project.
[4]NPOL – Lavochkin Association. This facility was the main organization in the USSR (and Russia) responsible for design, manufacture and flight control of all Luna, Venera, and Mars missions beginning in 1966. The first NPOL projects were led by General Designer G. N. Babakin (1914–1971). Prior to 1974, this facility had another designation (see text).

only successful lunar flight in 14 attempts during the six years from 1959 to 1966 was a lunar flyby by a Mars spacecraft, Zond 3, during its test flight in 1965. A second generation of lunar and planetary spacecraft had been developed by OKB-1 in 1962 for flights to Mars and Venus, and this spacecraft design was adapted for a lunar soft-landing mission. The first launch of this new lunar spacecraft occurred in January 1963, a full three years before the US was ready to attempt its first lunar soft landing mission. The spacecraft was stranded in Earth orbit and was followed by 10 mission failures in row over the next three years, half of which were caused by the launch vehicle and the other half due to spacecraft failures in flight.

The years 1960–1965 were as difficult for the Americans as they were for the USSR. The advantage went to the USSR because of its early successes and because its failures occurred in silence, while the Americans had no early success and failed in front of the entire world. After the Apollo program decision in 1961, the Americans devised a systematic, step-wise program for robot reconnaissance of the Moon before sending humans. This program consisted of a series of photographic impactors, mapping orbiters, and soft-landers. The US began its Ranger series of photographic impactors in 1961 with deep space tests of the new spacecraft (Figure 4). Both of these missions succumbed to launch vehicle failures. This was followed in 1962 with three Rangers carrying a capsule designed for a survivable hard landing, but all three spacecraft failed en route to the Moon. After having made further modifications to the spacecraft and a change of mission to a photo-

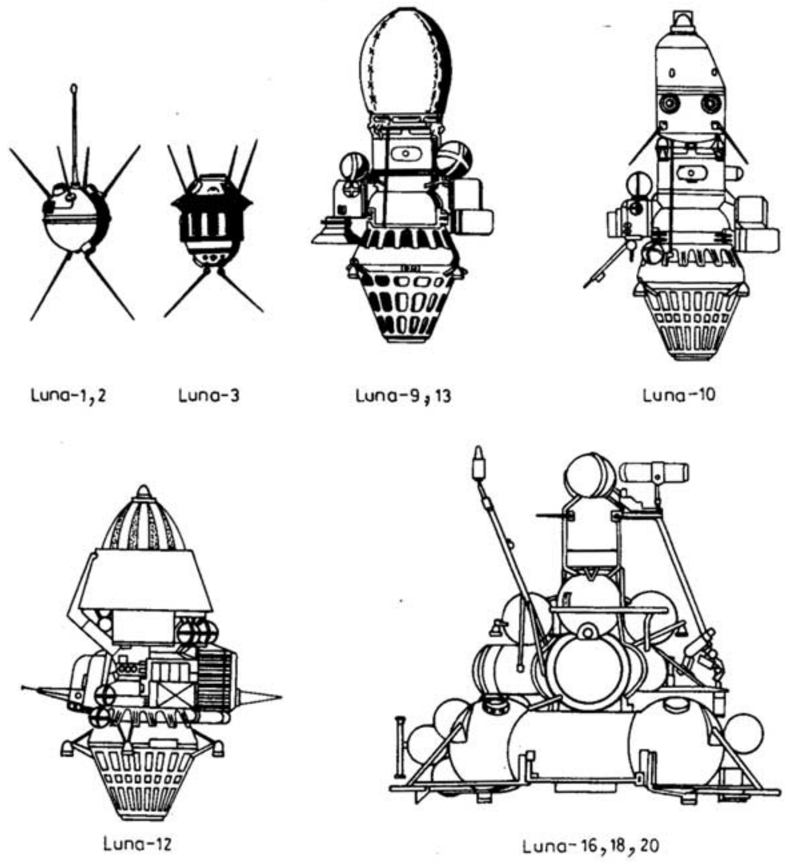

Figure 3. Generations of Soviet Lunar Spacecraft. Luna 1–2 impactors, Luna-3 circumlunar, Lunas 9, 13 soft landers, Luna 10, 12 orbiters, Lunas 16, 18, 20 sample return landers.

graphic impactor, two more were launched in 1964. The first flew flawlessly to the Moon but the cameras failed to turn on. The second, Ranger 7, became the first successful US mission to Moon in July 1964. Two more Ranger impactors were flown successfully in early 1965 and the US turned its attention to orbiters and soft landers.

4.2. The path to Apollo 1966–1969

The year 1966 saw the maturation of both the Soviet and American robotic lunar exploration programs. Ten missions were launched at the Moon with only two failures. The USSR succeeded with two lunar soft landings (Lunas 9 and 13) and three lunar orbiters (Lunas 10–12). The Americans succeeded in their first attempts at a lunar lander (Surveyor 1) and lunar photographic orbiters (Lunar Orbiters 1–2). Five Lunar Orbiters were flown successfully to the Moon in 1966–1967 and

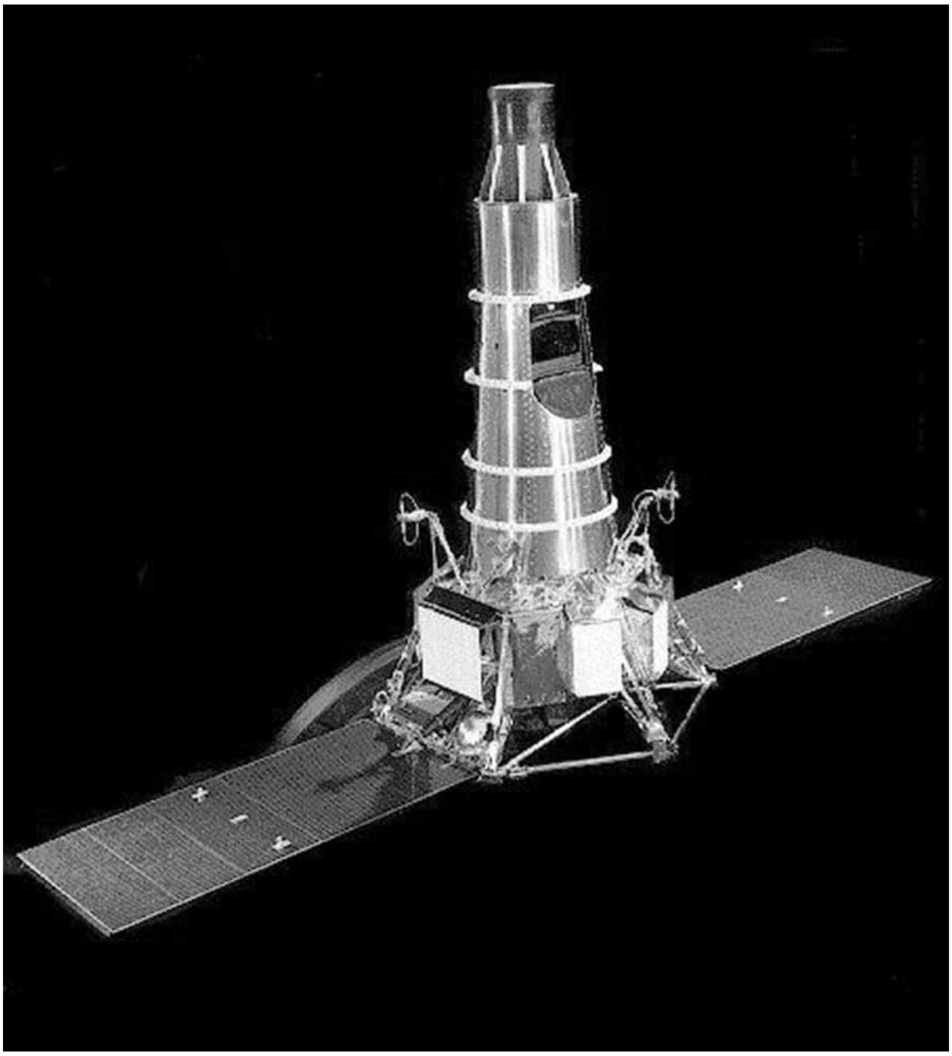

Figure 4. The US Ranger spacecraft.

fulfilled their mission to map the Moon for identification of Apollo landing sites. Examples of images from the Lunar Orbiters are presented in Figures 5 and 6. The Surveyor spacecraft followed by landing at sites selected from the Lunar Orbiter photos as representative of potential Apollo landing sites. Five of the seven Surveyor soft-lander missions were successful in the years 1966–1968. This monumental era in space exploration was capped by the successful Apollo 8, 10, 11 and 12 missions to the Moon in 1968–1969.

In 1966, responsibility for the Soviet robotic lunar and planetary program was transferred to NPOL. The first two NPOL lunar missions were successful: Luna 9 the first lunar soft landing, and Luna 10 the first lunar orbiter, both launched in

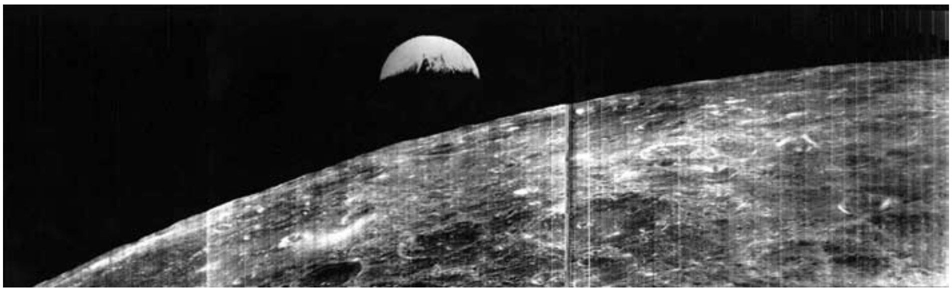

Figure 5. The first image of Earth taken from lunar orbit. Transmitted from Lunar Orbiter 1 in 1966.

1966. Luna 9 (Figures 7–9) was built by NPOL to the nearly the same print as the OKB-1 Luna 8, so both facilities shared in the glory. After these two flights, NPOL became independent of OKB-1, made its own contributions to the current generation Luna series through Luna 14, and then designed and built its own heavy lunar spacecraft series for sample return and a lunar rover.

After the Soviet decision in 1964 to compete with the Americans in a race to the Moon, OKB-1 turned almost all its attention to fulfilling that directive. In addition to the Luna reconnaissance landers and orbiters analogous to the American series, the USSR prepared for automated test flights of a piloted lunar spacecraft based on the Soyuz earth orbital system. The plan called for a series of Proton-launched 'Zond' automated circumlunar flights of the lunar Soyuz capsule followed by automated lunar orbital test flights launched on the giant N1 Moon rocket. The first of the Zond series beyond earth orbit, Zond 4, failed after re-entry following an otherwise satisfactory test flight to lunar distance in March 1968. After an intervening launch failure, the next flight in September 1968 was a success and the Zond 5 capsule was recovered intact. The USSR was now in a race with Apollo 8 to carry the first humans to the Moon. The third and final test before attempting a piloted flight, Zond 6, crashed on landing November 17, 1968. As a result, a piloted mission had to be postponed and the Americans won the race to be first at the Moon with Apollo 8 in late December 1968.

The year 1969 was a disaster for the Soviet lunar and planetary program, marked by a host of launch failures and a humiliating loss in the race to the Moon. Another Zond test flight was attempted in January 1969. The launch vehicle failed. The Proton-D was proving to be unreliable and there would be more critical failures throughout the spring of 1969. The Proton was not the only crucial launch vehicle to have problems. In February 1969 the USSR rolled its first N1 moon rocket to the launch pad, very late and long after the first tests of the American Saturn 5, but still hoping to win the race to the lunar surface. The test launch failed spectacularly on February 21 and a second vehicle exploded on July 3, just days before the Apollo 11 launch. Finally, a successful Zond 7 test flight was conducted in August 1969, after the Apollo 11 landing. However, by this time the wind had gone from the sails of the Soviet lunar cosmonaut program. The race to the Moon was over.

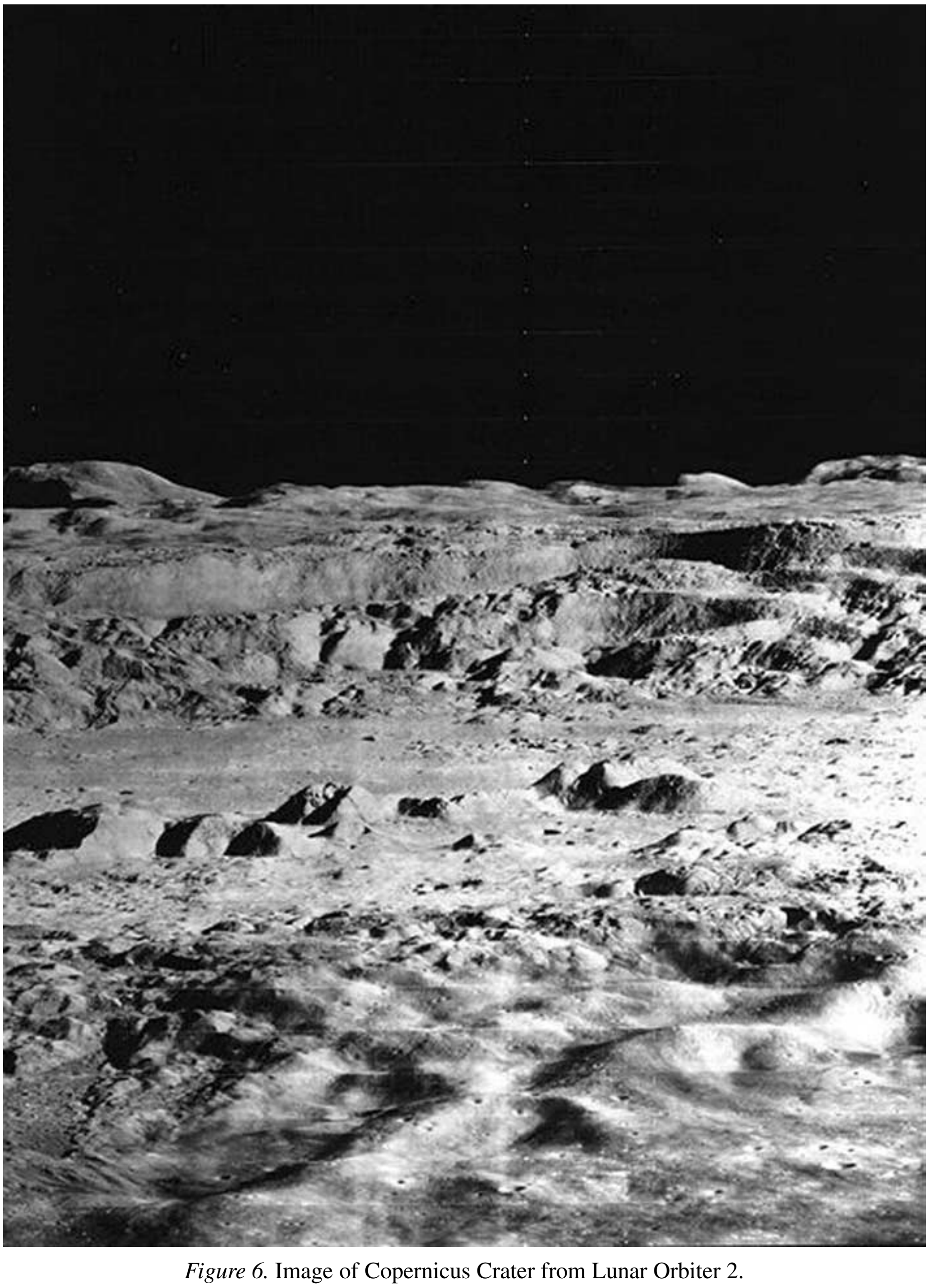

Figure 6. Image of Copernicus Crater from Lunar Orbiter 2.

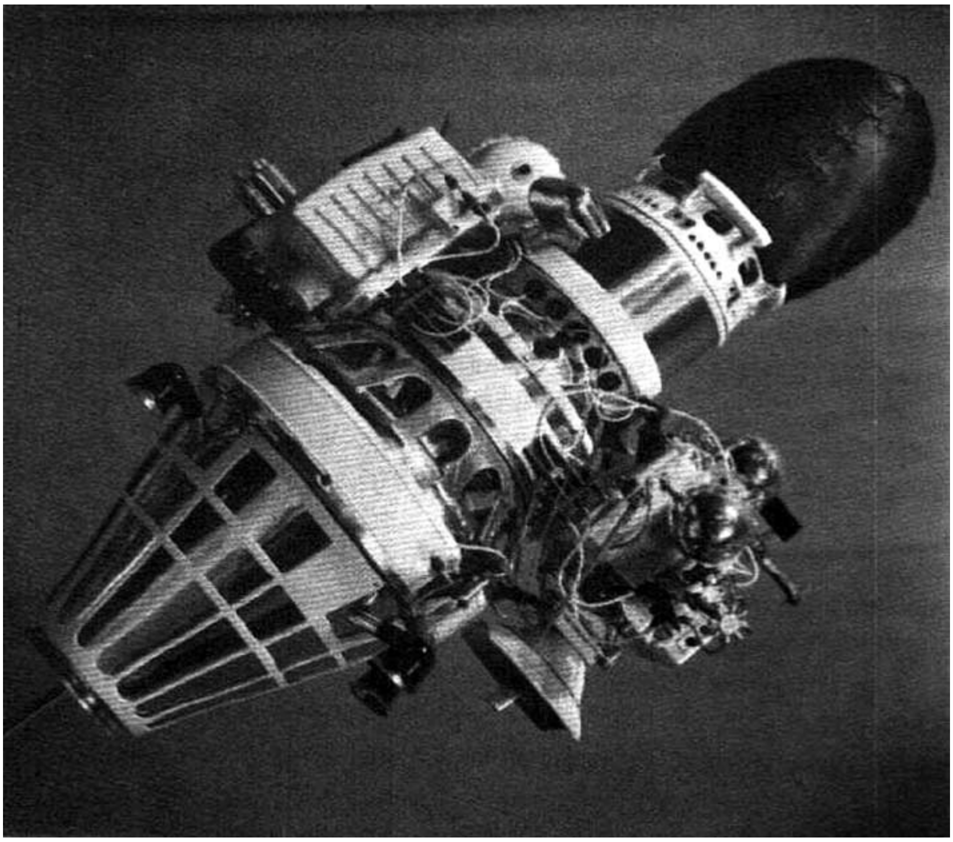

Figure 7. The Luna 9 spacecraft.

In the meantime, two days before the first N1 disaster, NPOL attempted to launch the first of its new heavy robotic lunar landing spacecraft on a Proton-D. The spacecraft carried a lunar rover of a type intended to have an active role in the lunar cosmonaut program. The Proton-D failed again. Realizing that the race to the lunar surface was all but over, the USSR initiated a backup tactic to return a lunar sample to earth before Apollo 11 using a robotic spacecraft. NPOL replaced the rover on its new heavy lunar lander spacecraft with a surface sampler and earth-return system. An attempt was made in mid-June to launch this new lunar sample return spacecraft, but once again the Proton-D launcher failed. A second spacecraft was readied and launched on July 13 as Luna 15. The Luna 15 spacecraft orbited the Moon as the Apollo astronauts walked on its surface and added drama to the adventure because its purpose was unknown and unannounced. The day after Neil Armstrong walked on the Moon, Luna 15 crashed into the surface on its landing attempt and its mission remained unknown for years afterward. Three additional attempts at robotic lunar sample return were made in September 1969, October 1969, and February 1970, but each were brought down by failures of the Proton-D.

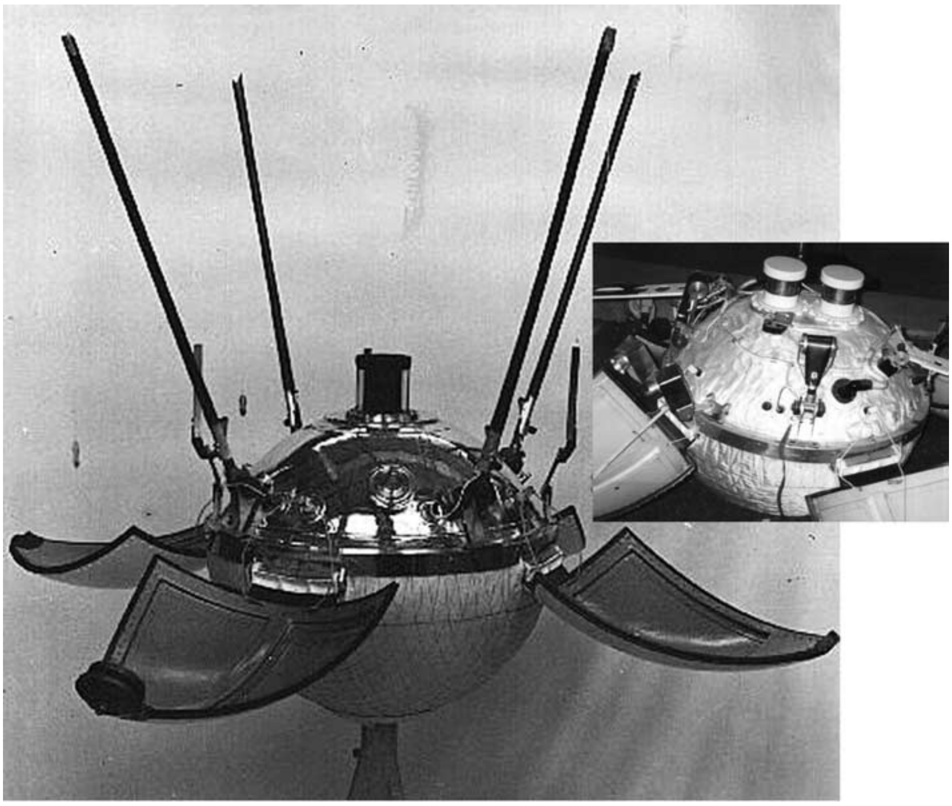

Figure 8. The Luna 9 and 13 lander modules. The Luna 13 lander had two cameras for stereographic imaging.

4.3. The post-Apollo years 1970–1976

The opening of the decade of the 1970s brought twilight to both the American Apollo program and the Soviet attempt to place its own cosmonauts on the Moon. In contrast, the year 1970 saw the maturation of the Soviet robotic lunar program and the accomplishment of scientific and engineering feats that were never attempted nor duplicated by the American lunar program.

In September 1970 the Soviet Luna 16 mission (Figure 10) succeeded in returning samples of the Moon to Earth. Luna 16 was followed two months later by Luna 17, which carried the first lunar rover. Lunokhod 1 (Figure 11) traversed over the lunar surface under remote control from Earth for almost an entire year. These two missions were bold, daring and highly productive scientifically. They would be considered superb even by today's standard. However, their political effect was minimal because they occurred in the shadow of the American Apollo landings. In October 1970 the USSR flew another successful Zond test flight without a pilot on board, even though it was considered ready, but the secret success was anti-

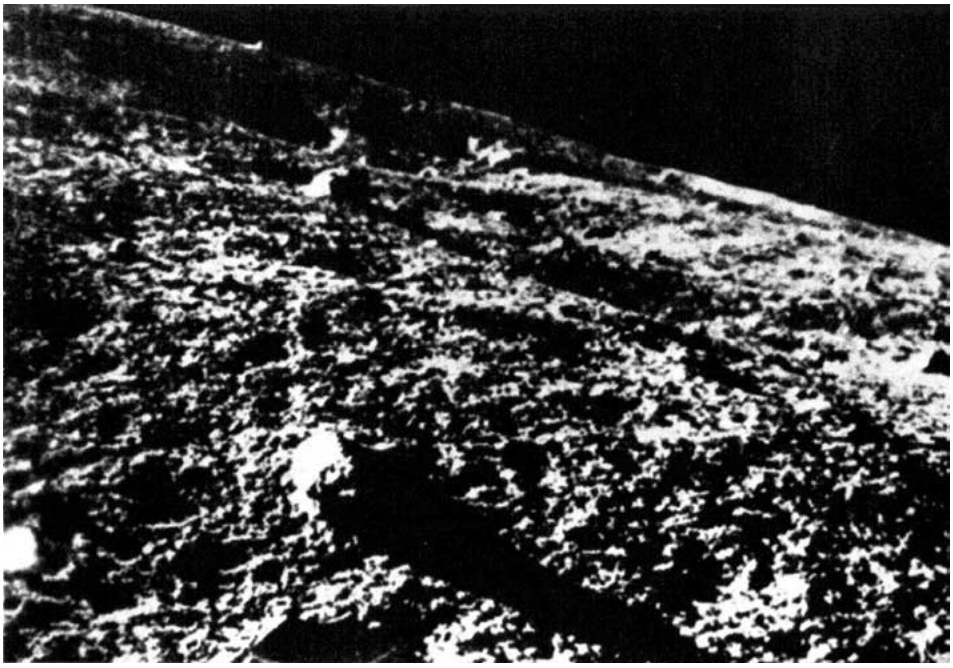

Figure 9. First image taken on the surface of the Moon by the Luna 9 lander.

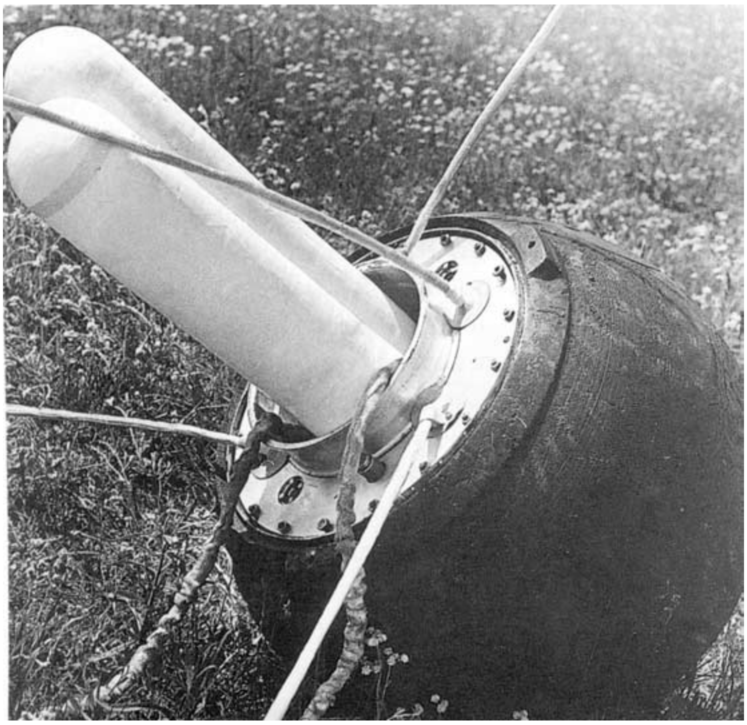

Figure 10. The Luna-16 return capsule after landing.

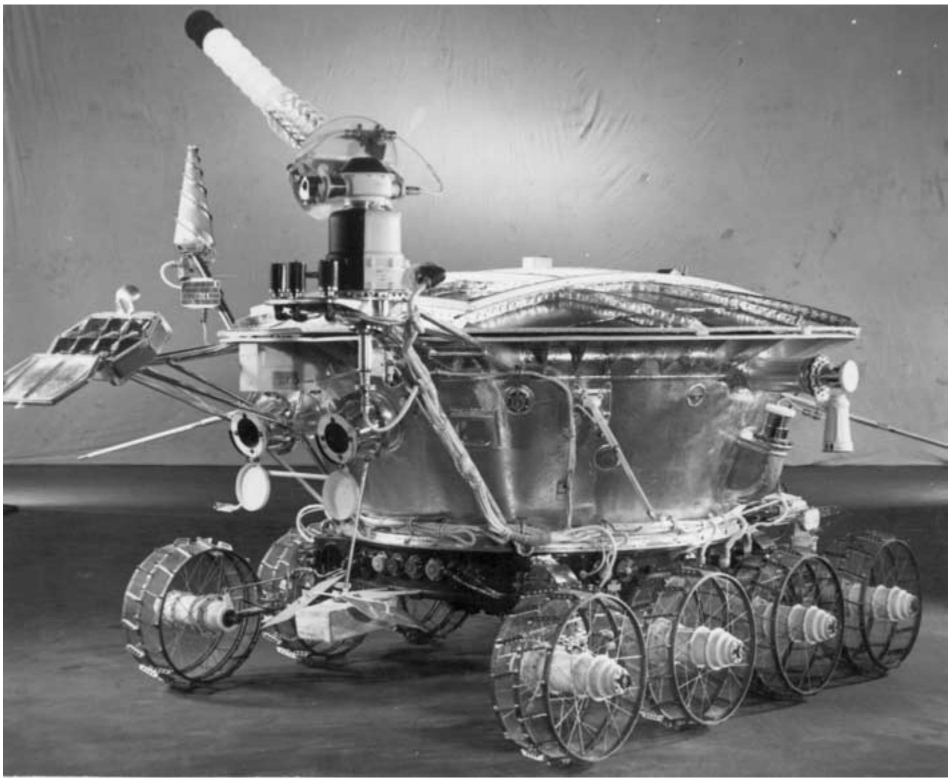

Figure 11. Lunokhod-1.

climactic and futile. Two more failed attempts to launch the N1 moon rocket in 1971–1972 delivered the coup-de-grace to the Soviet lunar cosmonaut program.

The Apollo program was completed in 1972 after six successful human landings on the Moon. One of the more interesting episodes occurred when Apollo 12 landed very near the Surveyor 3 robotic spacecraft in a test of precision landing (Figure 12). Apollo astronauts altogether delivered 381 kg of lunar samples to Earth. After Apollo 17, NASA ceased all flights to the Moon. The USSR flew five additional successful robotic missions: two orbiters, a second lunar rover Lunokhod-2, and two sample return missions, the last in 1976 returning a core sample from a depth of 2 meters.

Towards the end of this glorious era in lunar exploration, some of the rivalries between the competitors were set aside and the results of lunar exploration presented at an American-Soviet conference in Moscow in June 1974 (Vinogradov, 1975). One of the important conclusions was that the Moon has a thick crust, and that the Moon was entirely melted early in its history. This led to the idea that not only the Moon, but also the Earth and all terrestrial planets may have passed through an age in which their surfaces were covered with a magma ocean. Another important finding was that most ancient craters on the Moon are not more than 4 billions years

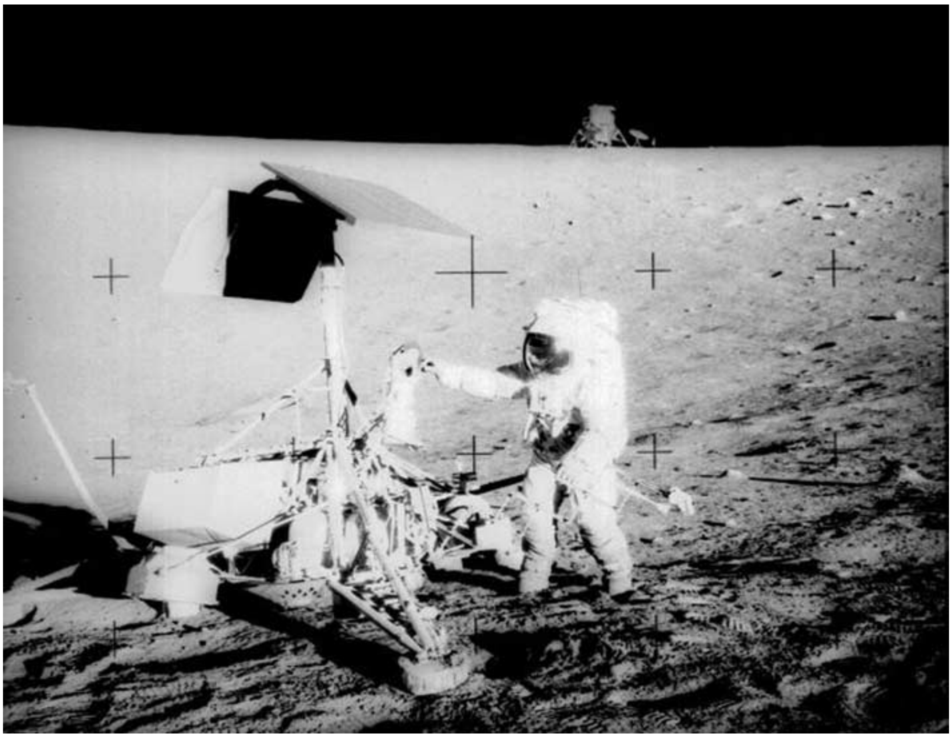

Figure 12. Astronaut Pete Conrad inspects Surveyor 3 after landing nearby on the Apollo 12 mission.

old, less than the age of the most ancient meteorites. Consequently, even the most ancient lunar craters appear to have been formed later than the age of planetary accretion. This meant that evidence of the accretion process had not been obtained, and the problem of lunar origin was still not solved. A hypothesis arose that lunar material was ejected from the Earth by collision with a large Mars-size body.

4.4. THE 1990S

After the termination of the Apollo program in 1972, and the series of Soviet robotic lunar missions in 1976, the Moon was set aside as a target for space exploration. In the 1970s and 1980s, the US was fully engaged in robotic planetary exploration from Mercury to the Outer Planets, and its human space program withdrew to no more than short Earth orbital missions with the Space Shuttle. The USSR turned its attention to robotic missions to Mars and Venus, and to development of Space Stations.

The interest lost in the Moon was revived somewhat in the 1990s when the US began to develop new spacecraft with more capability in a smaller package. The Moon became a target for a mission designed to test these new technologies, Clementine in 1994, and for a low-cost science mission, Lunar Prospector in 1998. Clementine, a joint development by NASA and the Department of Defense, operated a laser altimeter and spectral imaging cameras in lunar polar orbit for nearly three months, producing a wealth of new data including global maps of topography and of surface mineralogy in spectral ranges from the ultraviolet into the infrared. Lunar Prospector, the third in NASA's new line of low-cost 'Discovery' planetary missions, produced complementary global maps of geochemistry, magnetic and gravity fields. This mission discovered hydrogen in the soil in permanently shadowed regions of the poles, presumably due to trapped water.

The Moon also attracted the attention of emerging space powers. Japan's ISAS initiated its capability for planetary missions by flying the Hiten/Hagoromo mission to the Moon in 1990. The Hiten spacecraft deployed the Hagoromo orbiter on its flyby of the Moon, but no communication was ever received by Hagoromo. New missions to the Moon are now being planned by Japan, ESA and NASA.

5. Missions to Venus and Mercury

Table II lists events in Venus and Mercury exploration chronologically. Venus and Earth are sister planets. Venus is the closest planet to Earth, has nearly the same size and mass, and obtains only slightly more energy from the Sun. The planet is completely enshrouded in clouds and its surface perpetually hidden from view. Before the advent of the space program, the general similarity of the two planets led to speculation that under the impenetrable clouds of Venus lay a planetary surface similar to equatorial regions on our own planet – either a hot steamy tropical paradise partly or completely covered by an ocean, or a hot dry desert planet. The first planetary probes to Venus were to dispel such hopeful Earth-centric hypotheses. The first indication that the surface of Venus was drastically different from Earth came in 1956 when strong radio emissions were discovered equally bright at wavelengths of 3 cm and 10 cm, with a common temperature of about 600 K. These measurements implied thermal emission from either a hot surface or from the ionosphere. Radar observations of Venus were in better agreement with a hot surface, but the evidence was indirect. The first planetary missions to Venus were therefore directed at determining what the surface of the planet was like.

The first attempt to launch a spacecraft to Venus was by the USSR on February 4, 1961. This spacecraft was stranded in Earth orbit by the launch vehicle, but a second launch attempt on February 12 was successful and Venera 1 became the first spacecraft to be placed on an interplanetary trajectory. Venera 1 was a probe mission carrying a 'phase state sensor', an instrument similar to a carpentry level, to determine the attitude and dynamics of the probe after landing – stationary on a hard surface or bobbing with the waves on a sea. Unfortunately communications were lost with the spacecraft after only a few days. Opportunities to launch towards Venus occur about every 19 months. Soviet fascination with the nearest planet to Earth is marked by the fact that 29 launch attempts were made to Venus in 13 of the 16 available opportunities between their first launch attempt in 1961 and 1984,

TABLE II

Missions to Venus and Mercury in the 20th century

1961 (Celestial Window No. 1)				
[Venera] 1VA No. 1	probe	USSR	4 Feb 1961	Molniya
Identical to the Venera 1 spacecraft launched 8 days later. Failed to depart from low Earth orbit due to a fourth stage failure. Registered as Sputnik 7 in the US. The spacecraft carried science instruments and a pennant in a 'landing apparatus', an atmospheric entry probe expected to survive landing on the surface.				
Venera 1	probe	USSR	12 Feb 1961	Molniya
Communication failed in transit due to problems with attitude control and radio system failures (Chertok, 1999d).				
1962 (Celestial Window No. 2)				
Mariner 1	flyby	USA	22 July 1962	Atlas-Agena B
Launch vehicle failed.				
[Venera] 2MV-1 No. 3	atm/surf probe	USSR	25 Aug 1962	Molniya
A new modular spacecraft design for Venus and Mars missions. For this mission, the carrier vehicle carried a detachable entry probe expected to survive landing and carrying a pennant. Stranded in low Earth orbit when the fourth stage engine attitude control system failed (Chertok, 1999d). Registered as Sputnik 23 in the US.				
Mariner 2	flyby	USA	27 Aug 1962	Atlas-Agena B
First successful planetary mission. Flew by Venus at 34 745 km range on 14 Dec and discovered that its radio brightness was consistent with a hot surface.				
[Venera] 2MV-1 No. 4	atm/surf probe	USSR	1 Sept 1962	Molniya
Carried a pennant in an entry probe. Stranded in low Earth orbit due to a fourth stage failure (Chertok, 1999d). Registered as Sputnik 24 in the US.				
[Venera] 2MV-2 No. 1	flyby	USSR	12 Sept 1962	Molniya
Photo-flyby mission. Stranded in low Earth orbit when the third stage failed after 531 s (Chertok, 1999d). Registered as Sputnik 25 in the US.				
1964 (Celestial Window No. 3)				
[Venera] 3MV-1A No. 4A	test mission	USSR	19 Feb 1964	Molniya
Test launch of an improved spacecraft with its launch vehicle. Lost due to a third stage engine failure (Chertok, 1999d).				
[Venera] Cosmos 27	atm/surf probe	USSR	27 Mar 1964	Molniya
Stranded in low Earth orbit when the fourth stage engine did not ignite due to a power supply failure (Chertok, 1999d).				
[Venera] Zond 1	atm/surf probe	USSR	2 Apr 1964	Molniya
Spacecraft flew toward Venus, but communications failed in transit after two months. A leak in the pressurized 'orbital' section caused loss of thermal control and failure of the transmitters. Radio communications were conducted through the probe (Chertok, 1999d).				
1965 (Celestial Window No. 4)				
Venera 2	flyby	USSR	12 Nov 1965	Molniya
Flew by Venus at 23 950 km on Feb 27, 1966. Communications were lost during the Venus flyby due to a failure in the thermal control system. No data was returned (Chertok, 1999d).				

TABLE II

Continued

Venera 3 atm/surf probe USSR 16 Nov 1965 Molniya

Communications failed 17 days before arrival at Venus. The spacecraft carried a probe with science instruments and USSR pennant. First spacecraft to impact another planet on March 1, 1966.

[Venera] Cosmos 96 flyby USSR 23 Nov 1965 Molniya

Failed to depart from low Earth orbit. The third stage terminated improperly, and the fourth stage did not ignite due to unstable flight. The spacecraft separated with large disturbances (Chertok, 1999d).

1967 (Celestial Window No. 5)

Venera 4 atm/surf probe USSR 12 Jun 1967 Molniya

Full responsibility for planetary missions was transferred from OKB-1 to NPOL beginning with Venera 4, which became the first successful planetary atmospheric probe on 18 Oct 1967. Entered at 19N 38E on the night side and transmitted for 94 minutes in the atmosphere. The probe measured temperature, pressure, wind velocity, and CO_2, N_2 and H_2O content over 25–55 km on the night side of planet. Reported the atmosphere to consist of 90–95% CO2 and measured a temperature of 535 K before being crushed at 25 km altitude. No N2 was detected. The bus vehicle carried plasma and UV radiation experiments (Kuzmin and Marov, 1974).

Mariner 5 flyby USA 14 Jun 1967 Atlas-Agena D

Flew by Venus at 3990 km range on 19 Oct, one day after Venera 4, and conducted remote sensing experiments including radio occultation. The spacecraft carried a UV photometer and particles and fields instruments. Mariner 5 returned data on magnetic fields, atmosphere temperature, and found the atmosphere to consist of 85–99% CO_2 (Mariner 5, 1974).

[Venera] Cosmos 167 atm/surf probe USSR 17 Jun 1967 Molniya

Same design and science as Venera 4. Failed to depart from low Earth orbit (Chertok, 1999d).

1969 (Celestial Window No. 6)

Venera 5 atm/surf probe USSR 5 Jan 1969 Molniya

Successful atmospheric probe, entered the night side on 16 May 1969 at 3S 18E. The probe measured temperature, pressure, wind velocity, and CO_2, N2 and H_2O content over 25–55 km on the night side of the planet. Transmitted for 53 min in the atmosphere before being crushed at 18 km altitude. Flyby science identical to Venera 4 (Kuzmin and Marov, 1974).

Venera 6 atm/surf probe USSR 10 Jan 1969 Molniya

Same design and science as Venera 5. Successful atmospheric probe, entered the night side on 17 May 1969 at 5S 23E. The probe transmitted for 51 min in the atmosphere before being crushed at 18 km altitude. Venera 5 and 6 found an atmospheric composition of 93–97% CO_2, 2-5% N2 and less than 4% O_2 (Kuzmin and Marov, 1974).

1970 (Celestial Window No. 7)

Venera 7 atm/surf probe USSR 17 Aug 1970 Molniya

First successful planetary lander on 15 Dec 1970. Landed on the night side at 5S 351E and transmitted for 23 min from the surface. Measured a surface temperature of 747 K. No pressure data transmitted due to a failure in the data acquisition system. Venera 7 was the first Venera probe to survive atmospheric heat and pressure and reach the surface (Kuzmin and Marov, 1974).

TABLE II
Continued

[Venera] Cosmos 359 atm/surf probe USSR 22 Aug 1970 Molniya

Same design and science as Venera 7. Failed to depart from low Earth orbit.

1972 (Celestial Window No. 8)

Venera 8 atm/surf probe USSR 27 Mar 1972 Molniya

Landed 22 Jul 1972 on the dayside near the terminator at 10S 335E. Returned atmospheric temperature, pressure, wind speed, composition and light levels during descent. Transmitted data for 50 min. on the surface and reported a K-U-Th gamma ray surface composition analysis. Measured a surface temperature of 743 K and a surface pressure of 93 bar.

[Venera] Cosmos 482 atm/surf probe USSR 31 Mar 1972 Molniya

Same design and science as Venera 8. Failed to depart from low Earth orbit when the fourth stage misfired.

1973 (Celestial Window No. 9)

Mariner 10 flyby USA 3 Nov 1973 Atlas-Centaur

First spacecraft to use the gravity of one planet to reach another. Flew by Venus at 5310 km on 5 Feb 1974 enroute to Mercury. Conducted remote sensing of Venus in the IR and UV, imaging of clouds, and space physics experiments. Returned the first high-resolution UV images of Venus. Imaged 57% of the surface of Mercury in a single hemisphere during three successive flybys on 29 March, 1974, 21 September 1974 and 16 March 1975. Surface temperatures measured from 450 K on the dayside to 90 K on the night side. A weak, intrinsic magnetic field was discovered indicating a possible large fluid core (Dunne and Burgess, 1978).

1975 (Celestial Window No. 10)

Venera 9 orbiter/lander USSR 8 Jun 1975 Proton-D

New heavy spacecraft design using the Proton launcher. Dispatched a successful lander and orbited Venus on 22 Oct 1975. The Venera 9 mission yielded the first Venus orbiter, the first picture from the surface of other planet, and the first use of an orbiter as a relay for a planetary probe. The descent probe landed on the dayside at 32N 291E, and communicated through the orbiter for 53 min. The lander measured atmospheric composition, structure, and photometry on descent and obtained B/W images and K-U-Th gamma ray analyses on the surface. The orbiter returned imagery, IR-radiometry, spectrometry, photopolarimetry, radio occultation and plasma data (Venera 9 and 10, 1976).

Venera 10 orbiter/lander USSR 14 Jun 1975 Proton-D

Same design and science as Venera 9. Dispatched a successful lander on the dayside at 16N 291E, and orbited Venus on 25 Oct 1975. Venera 9 and 10 found the lower boundary of the clouds at 49 km and 3 distinct cloud layers at altitudes of 57–70 km, 52–57 km and 49–52 km. Both orbiters ceased operations in March 1976 (Venera 9 and 10, 1976).

1978 (Celestial Window No. 12)

Pioneer 12 orbiter USA 20 May 1978 Atlas-Centaur

Pioneer Venus 1. Orbited Venus on 4 Dec, 1978, and conducted remote sensing of the middle atmosphere and *in situ* measurements in the upper atmosphere. Conducted the first radar mapping of another planetary surface from a spacecraft. Found evidence for lightning but no magnetic field. Signal lost on 8 Oct 1992 shortly before entering the atmosphere (Pioneer Venus, 1980).

TABLE II
Continued

Pioneer 13	bus/probes	USA	8 Aug 1978	Atlas-Centaur
Pioneer Venus 2. The carrier bus dispatched one Large Probe and three Small Probes (North, Night, Day). All five vehicles entered separately on 9 Dec 1978. The bus returned data on the ionosphere before burn-up, and the probes returned data on atmospheric structure, chemical and isotope composition, fluxes of radiation, and cloud physics during descent. An anomaly in the relict noble gas abundances was found. Two atmospheric convection zones were found separated by a stable interval between 15 and 49 km. The probes were not designed to survive impact, but the small day probe continued to transmit for 68 min 37 s after impact (Pioneer Venus, 1980).				
Venera 11	flyby/lander	USSR	9 Sep 1978	Proton-D
Landed 25 Dec 1978 on the dayside at 14S 299E. Measured atmospheric temperature, pressure, wind velocity, spectra of short wavelength radiation, chemical and isotope composition, aerosols and thunderstorm activity. The surface imaging and soil acquisition systems failed. Contact was lost after 95 min on the surface. The flyby bus carried a UV spectrometer, plasma instruments and relayed communications from the lander (Venera 11 and 12, 1979).				
Venera 12	flyby/lander	USSR	14 Sep 1978	Proton-D
Same design and science as Venera 11. Landed 21 Dec 1978 on the dayside at 7S 294E. Conducted the same science as Venera 11 and included cloud particle composition. The surface imaging system also failed. Transmissions from the lander were received for 110 min until the flyby carrier went below the horizon (Venera 11 and 12, 1979).				
1981 (Celestial Window No. 14)				
Venera 13	flyby/lander	USSR	30 Oct 1981	Proton-D
Landed 1 Mar 1982 on the dayside at 7.5S 303.0E, and conducted atmospheric and cloud science, and both BW and color imagery of the surface. Surface XRF analysis found leucite basalt rare on Earth. The lander survived for 127 min (Venera 13 and 14, 1983).				
Venera 14	flyby/lander	USSR	4 Nov 1981	Proton-D
Same design and science as Venera 13. Landed 5 Mar 1982 on the dayside at 13.4S 310.2E. Conducted the same science as Venera 13. Surface XRF analysis found tholeiitic basalt similar to Earth mid-ocean ridges. The lander survived for 63 min (Venera 13 and 14, 1983).				
1983 (Celestial Window No. 15)				
Venera 15	orbiter	USSR	2 Jun 1983	Proton-D
Entered Venus orbit on 10 Oct. The orbiter returned radar images of the planet from 30N to the north pole at 1–2 km resolution. The middle atmosphere and clouds were examined by IR spectrometry (Venera 15 and 16, 1985).				
Venera 16	orbiter	USSR	7 Jun 1983	Proton-D
Same design and science as Venera 15. Entered Venus orbit on 14 Oct. Radar mapper with the same coverage and resolution as Venera 15. The IR instrument failed (Venera 15 and 16, 1985).				

TABLE II
Continued

1984 (Celestial Window No. 16)				
Vega 1	flyby/lander/balloon	USSR	15 Dec 1984	Proton-D
Conducted a Venus flyby on 11 June 1985 as a gravity assist maneuver to redirect the spacecraft to Halley's comet. During flyby, deployed an entry vehicle with a balloon and lander on the night side of the planet at 8.1N 176.7E. The lander conducted atmospheric science on descent. The balloon was released on descent and floated for 48 h over approximately 10 000 km at 54 km altitude measuring downdrafts of 1 m/s and average horizontal winds of 69 m/s. The lander conducted soil analysis with a gamma-spectrometer, but the X-ray fluorescence instrument failed. The spacecraft bus continued on to flyby Halley's Comet at 8890 km distance on 6 Mar 1986 (Reinhardt, 1986; Vega balloons, 1986; Vega 1 and 2, 1987).				
Vega 2	flyby/lander/balloon	USSR	21 Dec 1984	Proton-D
Same design and science as Vega-1. Deployed its balloon and lander in the night-side Venus atmosphere at 7.2S 179.4E on 15 Jun 1985 with similar results. Lander and balloon conducted the same measurements as Vega 1. Sample acquisition with XRF and gamma ray analysis on the surface found anorthosite-troctolite as in the lunar highlands but rare on Earth. The spacecraft bus continued on to flyby Halley's Comet at 8030 km distance on 9 Mar 1986 (Reinhardt, 1986; Vega balloons, 1986; Vega 1 and 2, 1987).				
1989 (Celestial Window No. 19)				
Magellan	orbiter	USA	4 May 1989	Shuttle-IUS[1]
The Venus radar mapper looped around the Sun 1.5 times before encountering Venus. Entered orbit on 10 Aug, 1990, and conducted high-resolution (to 300 m/pixel) remote radar mapping, altimetry, emissivity and gravity measurements of 98% of the surface. Also conducted radio occultations for atmospheric science. In later stages of its mission, Magellan became the first spacecraft to use aerobraking to circularize its orbit. Purposefully terminated in the atmosphere on 11 Oct 1994 (Magellan, 1992).				
Galileo	flyby	USA	18 Oct 1989	Shuttle-IUS[1]
Orbiter mission to Jupiter flew past Venus on 10 Feb 1990 using a gravity assist maneuver en route to Jupiter. Returned imagery and spectroscopy of near infra red night emission from the atmosphere below the cloud deck for the first time from a spacecraft.				
1997 (Celestial Window No. 24)				
Cassini-Huygens	flyby	USA	15 Oct 1997	Titan 4B
Joint NASA-ESA mission to Saturn and Titan. Flew past Venus twice, on 26 April 1998 and on 24 June 1999, using a gravity assist maneuver en route to Saturn. Returned remote imaging and spectroscopy of the atmosphere.				

[1]IUS is the solid rocket Interim Upper Stage used to achieve interplanetary trajectories after deployment of Galileo and Magellan from the Shuttle.

Figure 13. A painting of the Mariner 2 spacecraft.

when they ceased Venus exploration. The US attempted only 9 launches to Venus in 4 of the 16 opportunities, but was first to mount a successful mission, Mariner 2, on their second attempt in August 1962. The Mariner 1 spacecraft was lost earlier in July when the launch vehicle failed. All three Soviet attempts at Venus in 1962 succumbed to launch vehicle failures.

Mariner 2 (Figure 13) became the first successful planetary mission on December 14, 1962. Measurements of Venus' radio emission during the flyby were consistent with a very hot surface. After this mission, when it became clear that the surface of Venus was incredibly hot and nothing at all like the Earth, the US placed its emphasis on Mars exploration and dedicated only three more flight programs to the planet – Mariner 5 in 1967, the two Pioneer spacecraft in 1978, and Magellan in 1989.

OKB-1 attempted eleven launches to Venus between February 1961 and November 1965, but none of them were successful due either to failure of the launcher, or failure of the spacecraft on the way to the planet. A new generation Venera spacecraft with an entry probe was launched successfully towards Venus in April 1964, but it became clear immediately after launch that it would not reach its target because of a leak in the pressurized avionics module and the spacecraft was designated Zond 1 instead of Venera 2. Two spacecraft were successfully launched in the following opportunity in November 1965. The Venera 2 spacecraft conducted its flyby on February 27, 1966, but the communications system failed and no data was returned. Venera 3 fell silent 17 days before encounter and its probe entered the atmosphere silently on March 1, 1966. These were frustrating failures after having come so close to their goal.

Success at Venus finally came for the USSR in 1967 when Venera 4 became the first successful planetary atmospheric probe. The spacecraft flew perfectly to Venus and the probe separated from the spacecraft bus several days before arrival. The bus entered the atmosphere and burned up, while the probe entered the atmosphere, slowed for descent, opened a parachute and then made measurements of atmospheric properties down to an altitude 25 km. Data from the probe was transmitted directly to Earth using a low gain antenna at a rate of 1 bit/s during descent. The probe was destroyed at 25 km by the unanticipated high atmospheric pressure and temperature. The temperature measured at 25 km was 525 K so that the surface was even hotter (Kuzmin and Marov, 1974), confirming the inference from Mariner 2 that the high microwave emission temperatures were due to the surface and not the ionosphere. The US Mariner 5 flyby spacecraft arrived at Venus one day after Venera 4 and carried out remote sensing studies, returning data on the planetary magnetic field and information on the temperatures and composition of the atmosphere above about 40 km.

Whether consequential or not, the success of Venera 4 (Figure 14) coincided with the transfer of responsibility for robotic planetary missions from OKB-1 to NPOL. As in the case of Luna 9, technical documentation was prepared mainly by OKB-1 although NPOL designers made their own changes. All planetary spacecraft were built independently by NPOL after this transfer. NPOL planetary spacecraft were built in pairs (except the last, Mars 96) and two nearly identical spacecraft launched. The cost was only 15–20% more than for a single mission, and the overall reliability was much higher. NASA used this strategy as well in most cases prior to 1980. Subsequent abandonment of this strategy resulted in the loss of several planetary missions.

The USSR continued to send missions to Venus regularly after this initial success. Spacecraft with improved probe environmental protection followed Venera 4. Believing that Venera 4 reached the surface or quite near to it, and that prolonged exposure to high temperatures on a long descent was responsible for the failure of the probe, NPOL modified the next probe to resist higher g-loads and reduced the size of the parachute for a faster descent rate. The two subsequent missions

Figure 14. The Venera 4 probe, about one meter in diameter and weighing 383 kg.

launched in 1969, Venera 5 and 6, were both successful. The probes returned atmospheric data on temperature, pressure, winds and composition during descent, but again failed to reach the surface. The signals from each probe ceased at about the same pressure altitude near 18 km.

For the flight opportunity in 1970, the probe was strengthened to withstand pressures up to 180 atm and temperatures up to 540 °C. The science payload was reduced to accommodate the extra mass required by the strengthened capsule. These changes brought about the success the USSR had been looking for since 1961. On December 15, 1970, Venera 7 (Figure 15) made the first ever soft landing on another planet, and transmitted signals from the surface. However, a failure in the data acquisition system prevented all but temperature data to be transmitted, although in more detail than earlier missions. The surface temperature measured was 747 K.

For the 1972 opportunity the probe was lightened to withstand 105 atm instead of 180 atm, and the mass savings used for extra instrumentation. The first launch attempt was successful and Venera 8 conducted a successful mission to the surface, this time with a full instrument payload. All probes from Venera 4 to Venera 7 entered on the night side of the planet due to navigation requirements. However, a dayside landing was necessary to determine if enough solar light reached the surface for imaging purposes on future missions, so Venera 8 was intentionally landed on the illuminated part of the planet although very near to the terminator. On the surface, the probe reported a pressure of 93 bars, a temperature of 743 K, and light levels similar that on an overcast day on Earth, suitable for imaging and consistent with greenhouse theory for Venus. An analysis of the surface was also accomplished for the first time, yielding a basaltic rather than a granitic composi-

Figure 15. The Venera 7 spacecraft on a stand. Typical of the Venera 2–8 series, it consisted of a carrier vehicle with a propulsion module at one end (top) and a payload module, in this case a probe, attached at the other (bottom).

tion. The new data from Venera 8 provided the USSR with the information required to move on to a new and more complex surface investigation program.

In 1973, NPOL passed up a Venus launch opportunity for the first time in order to develop its new spacecraft. The US Mariner 10 was the only mission launched to Venus in the 1973 opportunity. Mariner 10 was the first mission to use a gravity assist by flying past one planet (Venus) to change velocity in order to reach another planet (Mercury). Without the use of this free energy assist from Venus, a mission to Mercury was not possible with the launch energies available at the time. Italian scientist Giuseppe ‘Bepi’ Colombo, working at JPL, discovered a special trajectory that would put the spacecraft in a circumsolar orbit after its first Mercury flyby, providing for multiple subsequent encounters with the planet albeit with the same hemisphere in view each time.

Mariner 10 conducted three flybys of Mercury obtaining photography of 57% of the planet in one hemisphere (see Figure 16), discovering its highly cratered lunar-like surface and measuring temperatures of 450 K on the dayside and 90 K on the night side. The biggest surprise was detection of an intrinsic planetary magnetic

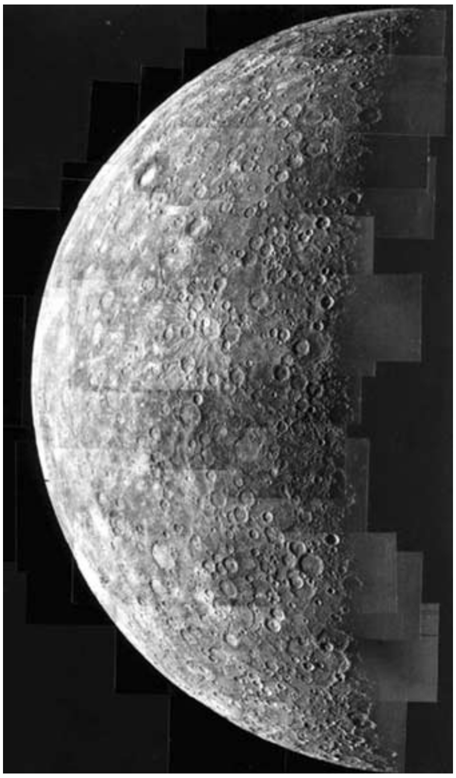

Figure 16. Mariner 10 mosaic of the approach hemisphere of Mercury.

field, indicating a very large iron core. Mariner 10 was the only mission conducted to Mercury during the 20th Century. However, NASA is developing the MESSENGER orbiter mission for launch in 2004, and ESA is planning an orbiter-lander mission for launch in 2010–2012 named Bepi Columbo in honor of the inventor of the Mariner 10 trajectory.

By 1975 the USSR was ready to launch its next generation Venera spacecraft built to take advantage of the same powerful Proton-D launcher that had been used to launch Lunar and Mars missions since 1969. The new Venera design was based on the large Mars spacecraft flown in 1971 and 1973. Figure 17 shows the Venera spacecraft, illustrating this new design. It consisted of a large carrier spacecraft that could be flown as an orbiter or flyby bus, depending on the energy required, and which served as a carrier vehicle for the entry system. The entry system was very different from the Mars design, utilizing a simple spherical entry capsule that could be separated in halves after entry for release of the lander vehicle contained inside. The carrier vehicle also acted as the communications relay for the lander during descent and on the surface.

The first of these spacecraft to be launched, Veneras 9 (Figure 17) and Venera 10 in 1975, completed their missions as did every Venus mission in this series

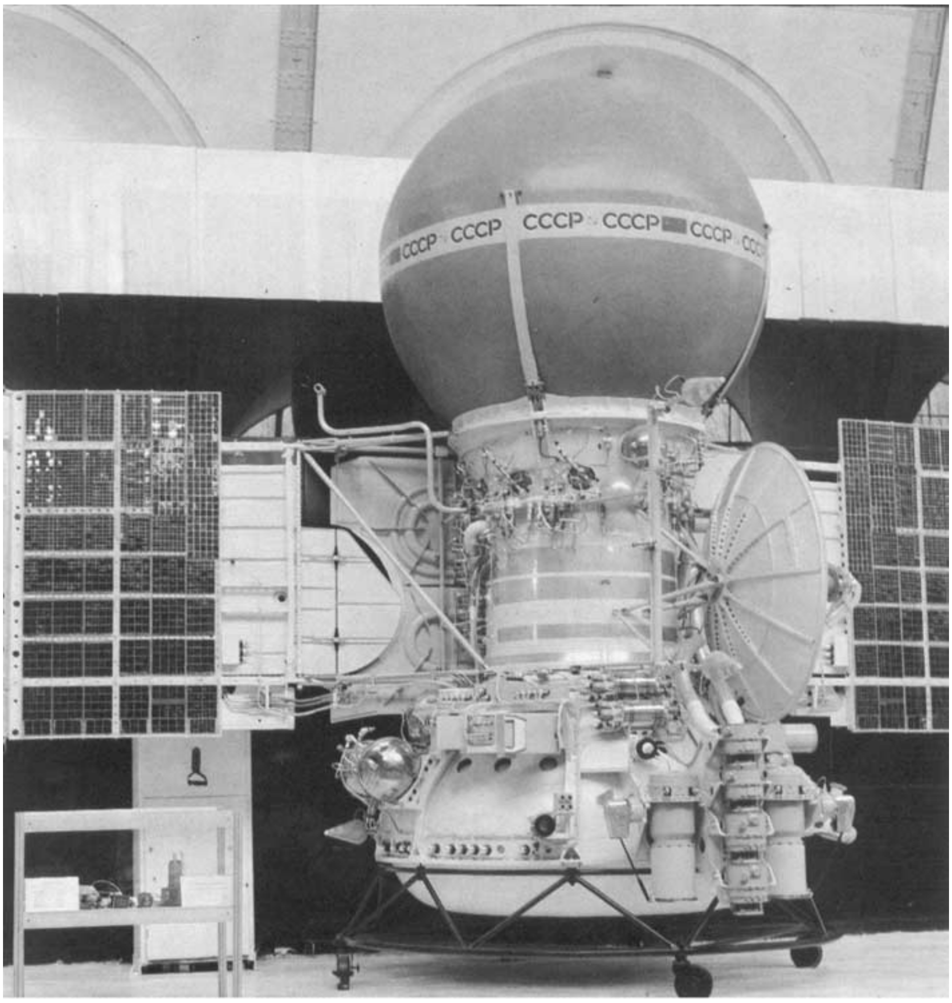

Figure 17. The Venera 9 spacecraft.

launched by the USSR through 1984. It is largely due to this highly successful series, Veneras 9–16 and the succeeding Vegas 1 and 2, that Venus became a Soviet niche in planetary exploration. Veneras 9 and 10 became the first Venus orbiters, and their landers transmitted the first panoramas of the Venus surface to Earth. Three additional Soviet dual lander missions were flown in 1978 (Veneras 11–12), 1981 (Veneras 13–14) and 1984 (Vegas 1-2) in which the carrier spacecraft flew past the planet as it relayed the lander data to Earth. The Venera 11 lander is shown in Figure 18. One of images of the surface of Venus from Soviet landers is presented in Figure 19. Two orbiter missions were carried out in 1983 (Veneras 15–16) in which the entry module was replaced with synthetic aperture radar antennas. The only Venus launch opportunities that were missed in this series were in 1977

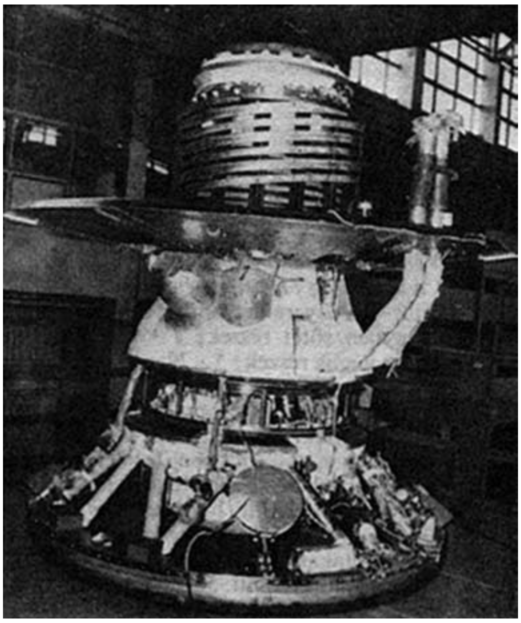

Figure 18. The Venera 11 lander prior to launch.

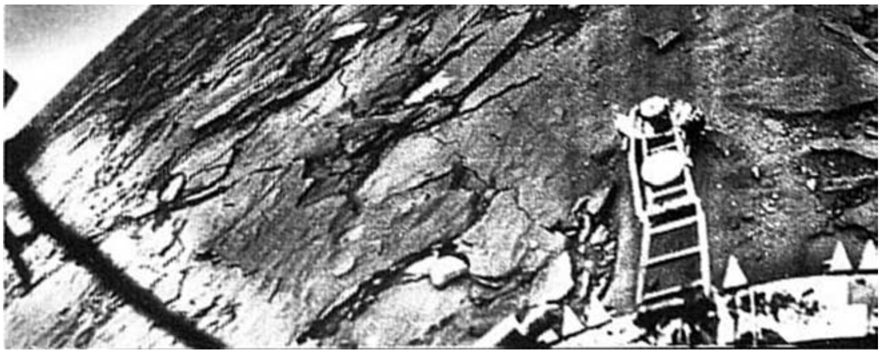

Figure 19. Image from Venera 14 on the surface of Venus. The soil penetrometer is in the foreground.

and 1980, skipped in order to develop new science instruments within budget limitations. This Venera series carried out unique investigations including panoramic images on the surface in black and white and in color, soil and atmosphere composition analysis, atmospheric structure, winds, aerosol and electrical properties, photometry and spectra of diffuse solar fluxes vs. altitude, and surface morphology at 1–2 km resolution from 30 N to the northern pole by the radar orbiters.

The last Soviet missions to Venus, Vega 1 and Vega 2 (1984), were more complex than their Venera predecessors. A drawing of the Vega spacecraft is shown in Figure 20. The entry system carried a separate balloon system for deployment and inflation on descent as well as the classic lander. After deploying the entry

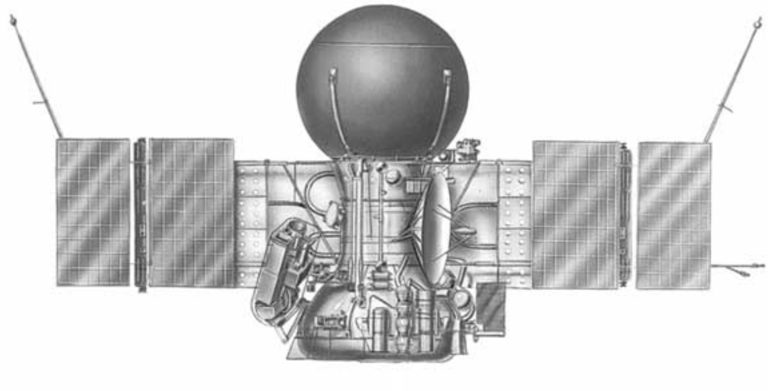

Figure 20. Drawing of the Vega 2 spacecraft.

system and relaying data from the lander, the flyby spacecraft were redirected to Halley's comet carrying a scientific payload for its study (Sagdeev *et al.*, 1986). The Halley objectives of these missions are described below in the section on small bodies of the solar system. Communication from the balloons was direct to Earth where an international network of antennas received the data and carried out Doppler tracking for wind information. The balloons successfully floated at about 54 km altitude for over 45 h, drifting approximately 9000–10 000 km mainly in the night-side atmosphere before losing battery power.

In the 1970s, for economic reasons, it was realized inside the USSR that it could not compete with the USA in every field of scientific research and M. V. Keldysh argued to concentrate in carefully selected narrow directions, accounting for the Soviet concentration and dominance in Venus exploration where the Americans seemed much less interested. Nevertheless, further exploration of Venus was cancelled by the USSR in 1985 as it turned its attention once again to Mars exploration. Results of earlier Soviet missions to Mars had been disappointing, but the scientists and engineers were emboldened by their record of success at Venus, the US seemed no longer particularly interested in Mars after the Viking missions, and the USSR now possessed a spacecraft capability that the US could no longer match.

In spite of US relative inattention to Venus, two small low-cost spacecraft (Figure 21) were flown in 1978 to make highly detailed investigations of the upper atmosphere and its interaction with the solar wind (variously known as Pioneer 12, Pioneer Venus 1, and Pioneer Venus Orbiter), and multi-point in-situ studies of the clouds and lower atmosphere with a multi-probe spacecraft (known as Pioneer 13 or Pioneer Venus 2). The Pioneer Venus Orbiter measured IR and UV radiation, fields and particles in the atmosphere and conducted low-resolution global radar altimetry of the surface. Its initial pericenter was very low (about 150 km) providing

Figure 21. The two Pioneer Venus spacecraft in assembly.

in situ measurements within the upper atmosphere. It orbited Venus until October 1992, sounding the middle atmosphere and ionosphere by radio occultation. The Pioneer 13 bus carried 1 large and 3 small atmospheric probes that were inserted nearly simultaneously into the lower atmosphere of Venus. The large probe measured chemical and isotopic composition of the atmosphere, and all probes measured vertical atmospheric structure, radiative fluxes, and cloud physical properties at different latitudes and solar longitudes. The Pioneer 13 carrier bus was used for in-situ investigations of the upper and middle atmosphere prior to burn-up.

The next NASA mission to Venus was launched 11 years later. The Magellan mission carried a radar instrument in polar elliptical orbit. Magellan obtained better resolution, to 300 m/pixel, and planetary coverage, 98%, than the earlier Venera 15 and 16 missions, returning a wealth of global high-resolution data including SAR imagery, radar altimetry, radio-emissivity, and gravity field. In the later stages of its mission, the Magellan spacecraft pioneered the aerobrake technique for orbital energy reduction to circularize its orbit. An illustration of Magellan results is shown in Figure 22.

Magellan was the last mission dedicated to Venus exploration in the 20th Century. Two other US missions made incidental measurements during gravity-assist flybys. Galileo made a Venus flyby in 1990 on its way to Jupiter, and returned near IR imagery and spectroscopy from the nighttime atmosphere below the cloud deck. Cassini/Huygens conducted flybys in 1998 and 1999, testing its remote sensing instrument suite for its 2004 arrival at Saturn.

Several books have been published giving general summaries of the results of this armada of Soviet and American Venus exploration missions (Hunten *et al.*, 1983; Bougher *et al.*, 1997; Barsukov *et al.*, 1992). The hot surface is dominated

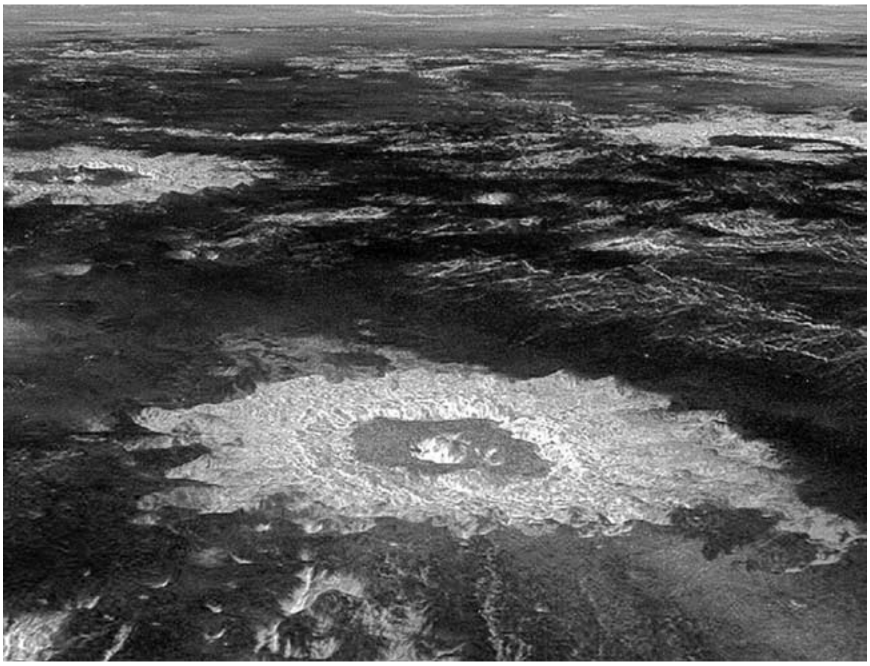

Figure 22. Flyover scene of the 'Crater Farm' on Venus constructed from Magellan radar imagery.

by plains with a large morphological diversity, including impact craters, young volcanic features, and traces of lava fluids. There are also mountains up to 10 km elevation. The surface age is very young, estimated to be about 500 millions years old, when a global resurfacing event may have occurred. The style of global volcanism on Venus is different from that on Earth and there is no obvious plate tectonics. Soil composition corresponds mainly to different types of basalt.

The most abundant atmospheric gas on Venus is CO_2. The global inventory of CO_2 on Venus is approximately the same as in carbonate deposits on the Earth. The water abundance is very low. There are interesting peculiarities in the content of some other volatiles including noble gases. Over the height range 0–60 km the temperature lapse rate is nearly adiabatic, but between approximately 30 and 49 km it is a little lower than the adiabat, resulting in two convective zones separated by a stable region. The principal feature of atmospheric general circulation is super-rotation with typical wind velocities of 60–120 m/s.

The whole planet is covered by layers of clouds in the height range from 49 to 70 km. However, a small but non-negligible part of the solar flux penetrates to the surface and heats the atmosphere due to the greenhouse effect. Venus has no intrinsic magnetic field and the solar wind interacts directly with the ionosphere. The upper atmosphere is relatively hot on the dayside but very cold at night. An interesting lesson learned from Venus exploration is that a terrestrial planet may have a climate very different from the Earth even with a more restricted energy supply (the effective temperature of Venus is lower than Earth due to increased cloud reflectivity).

There are still many questions about the nature of Venus, and after a decade of inattention plans are appearing for renewed exploration. An orbiter has been approved for study by ISAS and a surface investigation mission has been recommended for implementation in the US. Europe has also approved an ESA Venus orbiter mission.

6. Missions to Mars

Table III lists events in Mars exploration chronologically. Mars is more like Earth than any other planet, including Venus. In its distant past, Mars may have had a denser atmosphere, a warmer climate and liquid water on the surface. It remains possible that life may have arisen on early Mars, and it is also possible, although less probable, that microbial life currently exists on Mars hidden from view below the surface where liquid water may be available.

TABLE III

Missions to Mars in the 20th century

1960 (Celestial Window No. 1)				
[Mars] 1M No. 1	flyby	USSR	10 Oct 1960	Molniya
Did not achieve Earth orbit due to third stage rocket failure at 309.9 s into the flight (Chertok, 1999d).				
[Mars] 1M No. 2	flyby	USSR	14 Oct 1960	Molniya
Did not achieve Earth orbit. Third stage rocket failed due to oxidizer shut-off valve leak (Chertok, 1999d).				
1962 (Celestial Window No. 2)				
[Mars] 2MV-4 No. 3	flyby	USSR	24 Oct 1962	Molniya
Failed to depart from low Earth orbit. Fourth stage turbo-pump failed at ignition and the stage exploded. Designated Sputnik 29 in the US (Chertok, 1999d).				
Mars 1	flyby	USSR	1 Nov 1962	Molniya
Photo-flyby mission. First mission launched towards Mars. Communications failed in transit at 106 million km on March 21, 1963, when the antenna could no longer point at Earth. Silent s/c passed Mars at 195 000 km on June 19, 1963 (Chertok, 1999d).				
[Mars] 2MV-3 No. 1	probe	USSR	4 Nov 1962	Molniya
Failed to depart from low Earth orbit. Fourth stage failure disintegrated the vehicle. Designated Sputnik 31 in the US (Chertok, 1999d).				
1963 (No Celestial Window)				
[Mars] Cosmos 21	test mission	USSR	11 Nov 1963	Molniya
Test launch of a new spacecraft with its launch vehicle. Mars not available on this launch date. Lost 1330 s into the flight when the 4th stage separated at an incorrect attitude and its propulsion system failed. The spacecraft was later found adrift in low earth orbit (Chertok, 1999d).				

TABLE III
Continued

1964 (Celestial Window No. 3)

Mariner 3	flyby	USA	5 Nov 1964	Atlas-Agena D

The shroud failed to jettison properly, so that the solar panels did not open and proper solar-pointing attitude was not attained. Transmissions ceased after 9 h.

Mariner 4	flyby	USA	28 Nov 1964	Atlas-Agena D

First successful Mars mission. Flew by Mars within 9846 km of the surface on 14 July 1965 US time. The camera first shuttered at 00:18:33 15 Nov UT and returned 22 pictures covering about 1% of Mars' surface. Instrument complement: TV camera, solar plasma probe, ionization chamber, trapped radiation detector, helium vector magnetometer, cosmic ray telescope and cosmic dust detector. Found no intrinsic magnetic field, a thin atmosphere of 5–10 mbar CO_2, and a cratered surface.

[Mars] Zond 2	flyby	USSR	30 Nov 1964	Molniya

Photo-flyby mission. Communications failed in transit after one month. The solar panels did not open completely and the on-board control system had early failures. The spacecraft flew by Mars at 650 000 km distance and entered solar orbit (Chertok, 1999d).

1965 (No Celestial Window)

[Mars] Zond 3	test mission	USSR	18 Jul 1965	Molniya

Test mission using a spacecraft identical to Zond 2 that missed its 1964 launch opportunity. Mars was not in proper position for an encounter. The spacecraft failed after 7.5 months before reaching Mars distance. Earlier on 20 July, Zond 3 flew past the moon at 9219 km and returned 28 photos of the lunar farside (Chertok, 1999d).

1969 (Celestial Window No. 5)

Mariner 6	flyby	USA	25 Feb 1969	Atlas-Centaur

Flew by Mars at 3437 km above the equatorial region on 30 Jul 1969 and returned 75 pictures. Conducted measurements of surface and atmospheric temperature, surface composition, and atmospheric pressure.

Mariner 7	flyby	USA	27 Mar 1969	Atlas-Centaur

Flew by Mars at 3551 km distance near the south polar region on 4 Aug 1969 and returned 126 pictures of southern hemisphere and south pole. Mariner 7 carried the same science payload as Mariner 6.

[Mars] M-69A	orbiter	USSR	27 March 1969	Proton-D

A planned atmospheric probe was deleted due to mass and test problems. Did not achieve Earth orbit due to a 3rd stage explosion (Perminov, 1999).

[Mars] M-69B	orbiter	USSR	2 April 1969	Proton-D

A planned atmospheric probe deleted due to mass and test problems. Launch failed due to an explosion of one of the six booster engines at launch (Perminov, 1999).

1971 (Celestial Window No. 6)

Mariner 8	orbiter	USA	9 May 1971	Atlas-Centaur

Failed to reach Earth orbit due to failure of the Centaur upper stage.

TABLE III
Continued

[Mars] Cosmos 419	orbiter	USSR	10 May 1971	Proton-D

Left in low Earth orbit due to failure of the 4th stage to re-ignite for interplanetary injection. Resulted in loss of the planned orbital radar beacon at Mars and therefore navigation accuracy at Mars for the subsequent arrival of the Mars 2 and 3 entry vehicles (Perminov, 1999).

Mars 2	orbiter/lander	USSR	19 May 1971	Proton-D

Released entry vehicle and entered Mars orbit on 27 Nov 1971. This first attempt at a Mars landing crashed at 44.2S 313.2W due to imprecise targeting of the entry vehicle, resulting in an excessive entry angle and impact before parachute deployment. Mars 2 was the first human artifact on Mars. The orbiter returned data for 4 months (Perminov, 1999).

Mars 3	orbiter/lander	USSR	28 May 1971	Proton-D

Released entry vehicle and entered Mars orbit on 2 Dec 1971. Mars 3 achieved the first successful landing on Mars 2 Dec 1971 at 45S 158W. The lander activated 90 s after landing but failed after sending 20 s of a gray, featureless image to the orbiter. The suspected cause was transmitter failure due to coronal discharge in the global dust storm. The orbiter returned data on surface temperature and atmospheric composition for four months. Both Mars 2 and 3 missions were terminated in Aug 1972 (Perminov, 1999; Moroz, 1978; Snyder and Moroz, 1992).

Mariner 9	orbiter	USA	30 May 1971	Atlas-Centaur

First successful planetary orbiter. Photographic mapper was placed into Mars orbit on 13 Nov 1971 (engine shutdown at 00:15:40 14 Nov UT). Many of its experiments were delayed until the global dust storm encountered at arrival dissipated. Returned 7329 orbital photos of 100% of Mars including the first close range images of Phobos and Deimos. Dry river and channel-like features were discovered. The spacecraft exhausted its attitude control gas on 27 Oct 1972.

1973 (Celestial Window No. 7)

Mars 4	orbiter	USSR	21 Jul 1973	Proton-D

Failed to achieve Mars orbit on 10 Feb 1974 due to an on-board engine failure. Flew past Mars at 2200 km and returned flyby images and radio occultation data (Perminov, 1999; Mars 5, 1975; Sidorenko, 1980).

Mars 5	orbiter	USSR	25 Jul 1973	Proton-D

Orbited Mars on 12 Feb 1974. Returned photos of the southern hemisphere and other data. Failed after 22 orbits on Feb 28 due to loss of pressurization in the transmitter module (Perminov, 1999; Mars5, 1975; Sidorenko, 1980).

Mars 6	flyby/lander	USSR	5 Aug 1973	Proton-D

Partial telemetry failure after 2 months. Spacecraft operated autonomously, completed navigation and course corrections and delivered an entry vehicle on 12 Mar 1974 to 23.9S 19.4W. Atmospheric data was transmitted to Earth during parachute descent via the Mars 6 flyby carrier, but communications were lost 0.3 sec before landing (Perminov, 1999; Moroz, 1978; Snyder and Moroz, 1992).

Mars 7	flyby/lander	USSR	9 Aug 1973	Proton-D

Failed to deliver its entry vehicle to the proper encounter trajectory on 9 Mar 1974 due to a transitor failure. Entry vehicle missed the planet by 1300 km (Perminov, 1999; Snyder and Moroz, 1992).

TABLE III
Continued

1975 (Celestial Window No. 8)				
Viking 1	orbiter/lander	USA	20 Aug 1975	Titan 3E Centaur
Orbited Mars on 19 Jun 1976. Dispatched a successful lander to Chryse Planitia (22.27N 47.97W) on 20 Jul 1976. The orbiter depleted its propellant on 7 Aug 1980. The lander was accidentally shut down on 13 Nov 1982 and not recovered. The Viking 1 and 2 landers produced detailed and panoramic color images and monitored the weather. They conducted a search for organic material and microorganisms generally considered negative (Viking 1 and 2, 1977; Spitzer, 1980).				
Viking 2	orbiter/lander	USA	9 Sep 1975	Titan 3E Centaur
Orbited Mars on 7 Aug 1976. Dispatched a successful lander to Utopia Planitia (47.67N 225.74W) on 3 Sep 1976. The orbiter powered down on 25 Jul 1978 when attitude control was lost due to a gas leak. The lander ceased functioning on 12 Apr 1980 due to battery degeneration. The Viking 1 and 2 orbiters together returned over 52 000 photos covering about 97% of Mars. The landers returned over 4500 images, extensive weather data and found no consensus evidence of life or organics on the surface (Viking 1 and 2, 1977; Spitzer, 1980).				
1988 (Celestial Window No. 14)				
Phobos 1	orbiter	USSR	7 Jul 1988	Proton-D
Both Phobos 1 and 2 were Mars orbiters intended for multiple flybys of Phobos with both passive remote sensing and active remote sampling including deployment of two small Phobos landers. Phobos 1 was lost by a command error on 2 Sep 1988 while en route to Mars.				
Phobos 2	orbiter	USSR	12 Jul 1988	Proton-D
Entered Mars orbit on 30 Jan 1989. The spacecraft was lost due to a computer software failure in Mars orbit on March 27, 1989, at just 800 km distance from its first close flyby of Phobos. The spacecraft had previously passed Phobos at 200–600 km range. Phobos 2 carried an extensive set of international instruments and returned more remote sensing observations of Mars and Phobos than any previous Soviet mission (Phobos, 1989).				
1992 (Celestial Window No. 16)				
Mars Observer	orbiter	USA	25 Sep 1992	Titan 3C
Propulsion system failed on 21 Aug 1993, 3 days prior to Mars orbit insertion, destroying the spacecraft.				
1996 (Celestial Window No. 18)				
Mars Global Surveyor	orbiter	USA	7 Nov 1996	Delta 2
Entered Mars orbit on 11 Sep 1997, and over the next 18 months used aerobraking to achieve a close mapping orbit. Daily mapping began in March 1999. Continues to return data on surface morphology, topography, composition, gravity, atmospheric dynamics and magnetic field.				
Mars 96	orbiter/landers	Russia	16 Nov 1996	Proton-D
An orbiter carrying two deployable landers and two deployable penetrators. The fourth stage ignited prematurely and the spacecraft reentered the atmosphere. Carried many international instruments.				

TABLE III
Continued

Mars Pathfinder	lander/rover	USA	4 Dec 1996	Delta 2
Landed successfully using air bags in the rocky Ares Vallis flood plain on 4 Jul 1997 at 16:57 UT. Impacted at 18 m/s. The first bounce was 15 m high, followed by at least 15 more bounces. The spacecraft also rolled 2.5 times before stopping 1 km from the impact site. The final resting point was 19.33N 33.55W. A six-wheeled 'Sojourner' micro-rover was deployed on 6 July at 05:40 UT. The rover communicated through the lander and carried a rock elemental composition instrument and a stereo camera. The last successful transmission occurred on Sept 27, 1997. The lander returned data from a color stereo imager, a soil magnetism experiment and a meteorological package for pressure, temperature, wind speed, and direction at three vertical levels. 16 000 images returned were from the lander and 550 from the rover. 15 soil and chemical analyses were conducted (Mars Pathfinder, 1997).				
1998 (Celestial Window No. 19)				
Nozomi	orbiter	Japan	3 Jul 1998	M5
ISAS mission. Left in parking orbit until December 1998, the spacecraft suffered a misfire during the planetary injection burn and required several Earth flyby gravity assists to reach Mars. Now enroute, it arrives in December 2003.				
Mars Climate Orbiter	orbiter	USA	11 Dec 1998	Delta 2
Failed to achieve Mars orbit 23 Sep 1999 due to a navigation error, sending the spacecraft too low in the atmosphere during the propulsive braking maneuver.				
1999 (Celestial Window No. 19)				
Mars Polar Lander	lander/penetrators	USA	3 Jan 1999	Delta 2
Failed during entry and landing after separation from the carrier vehicle on 3 Dec 1999. The carrier also released two experimental Deep Space 2 Probes for separate entry. These two hard microlander-penetrators also failed. No communication was received from MPL or the DS-2 probes after separation. MPL was probably lost at landing leg deployment due to a software failure and subsequent engine shutdown.				

The hypothesis that Mars may harbor life was proposed at the end of 19th Century to explain a seasonal variation of contrast between dark and light regions. The idea of a habitable Mars grew beyond reasonable bounds when the American astronomer Percival Lowell claimed to have seen artificial canals on Mars. Early science fiction drew heavily from Lowell's claims and created the popular notion that Mars might be inhabited by intelligent beings of generally hostile intent. These notions survived throughout the 20th Century until the first mission to the planet discovered the cratered southern highlands, more like the Moon than the Earth, and found inhospitable atmospheric temperatures and pressures. Even so, Mars remains a high priority for planetary exploration today. While it is clear that there is no high-order life on the surface, one of the long-term goals of Mars exploration is to search for traces of a past or current biosphere.

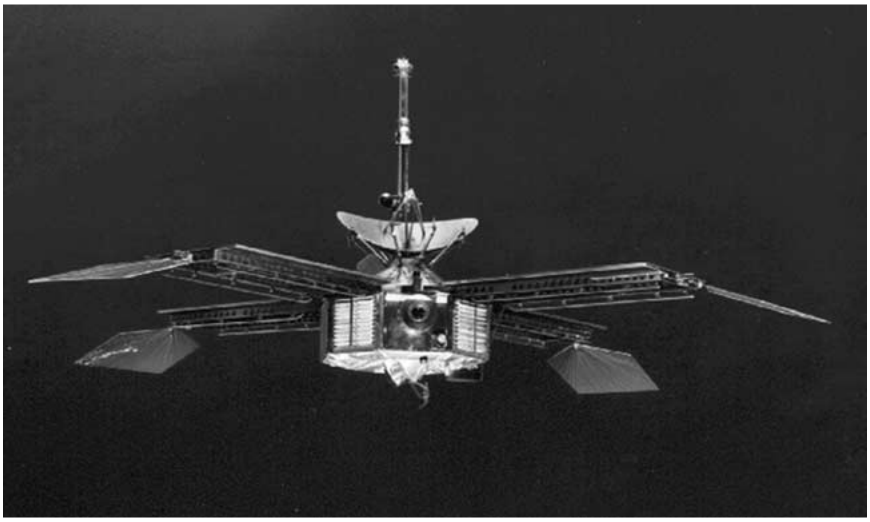

Figure 23. The Mariner 4 spacecraft.

The first ever attempt to launch a spacecraft to another planet was on October 10, 1960, by the USSR. The USSR attempted twice in 1960 to launch a flyby mission to Mars, but the third stage of the new Molniya launch vehicle failed both times. Four months later, two similar spacecraft modified as probes were launched to Venus. One of them became Venera 1. In the next 18 months OKB-1 built a new and more capable modular spacecraft designed to be flown to either Mars or Venus and to carry a variety of different payloads. In 1962 the launch opportunities for both planets were close together and the USSR launched six of these new spacecraft, three each to Venus and Mars. The only successful launch was the Mars 1 flyby spacecraft, which flew half way to the planet before communications were lost. After the poor results with this new spacecraft in 1962, OKB-1 made a number of improvements and a test mission was launched in 1963 intended for flight to Mars distance. Unfortunately, the test mission failed when the spacecraft was stranded in Earth orbit due to a problem with the 4th stage of the Molniya.

The US took much longer to prepare its first mission to Mars. The US launched its first Mars spacecraft, Mariner 3, in early November 1964. The spacecraft was lost when the launch vehicle shroud did not jettison properly. The Mariner 4 spacecraft (Figure 23) was successfully launched at the end of the month to become the first successful mission to Mars. On July 14, 1965, the spacecraft flew less than 10 000 km from the surface and sent back 22 images revealing a cratered surface and a thin atmosphere of carbon dioxide with a surface pressure less than 1/100 that of Earth. Examples of Mariner 4 images are shown in Figure 24.

The USSR also launched a flyby mission to Mars two days after Mariner 4. There were immediate problems onboard the spacecraft and OKB-1 named it Zond 2 after realizing that it would not survive to reach its target. Communications

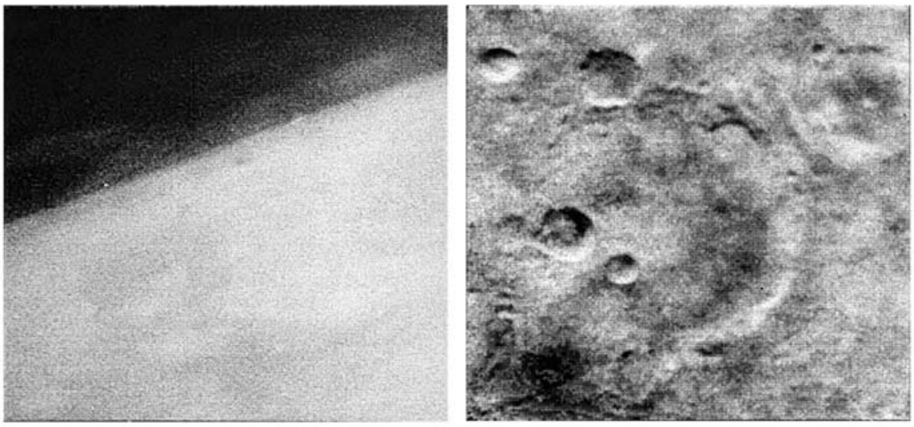

Figure 24. Mariner 4 images, (a) first ever image of Mars taken at the limb of the planet revealing high clouds, (b) image no. 11, showing large craters on the surface, famous for dashing hopes of a living planet.

ceased from Zond 2 after a month of flight. The Soviet planetary program had now failed in eight launches to Venus and seven launches to Mars over five years. Their new multi-mission spacecraft, when it survived the launch vehicle, had failed in flight three times. In addition, there had been seven Luna mission failures since Luna 3 in 1959, so that at the end of 1964 the USSR was on a five-year run of 22 straight lunar and planetary mission losses. None of this was known publically in the West, nor was it known in the USSR except to those directly involved in the activity. Such a poor record would never have been tolerated in the US, but it became a feature of the Soviet program that it could rebound from this and future such internally demoralizing problems. Exacerbating the disappointment in early 1965 was the realization that in spite of a large and early Soviet lead, the Americans had beaten the USSR to both Venus and Mars with successful missions. In July 1965 another purposeful test mission was flown. Zond 3 was launched successfully, and the spacecraft performed well in conducting its test objectives at the Moon, but failed after seven months before reaching Mars distance. Later in 1965 the Veneras 2 and 3 spacecraft were successfully launched and came agonizingly close to completing their missions.

With the near success of Veneras 2 and 3, the USSR concentrated its efforts on carrying out a successful mission at Venus and gave up on using this spacecraft for Mars. They skipped a flight opportunity in 1967 and labored on a much bolder and more risky plan for Mars, designing a large spacecraft to take advantage of their new powerful Proton booster. The goal was to land an instrumented capsule on the surface of the planet to take panoramic images of the scene, analyze the atmosphere and surface characteristics, and to look for signs of life. The lander was to be carried by a large orbiter, which would conduct global remote sensing of the planet and make close flybys of Phobos and Deimos. This plan was developed by Babakin in March 1966 shortly after the transfer of responsibility for robotic lunar and planetary missions to NPOL and was to be carried out in the 1969 and 1971 launch opportunities. It was an audacious plan for a program that had not yet mounted a successful mission to Mars after eight attempts.

The US was planning its own assault on Mars, without any strategic plan or timetable, but ultimately also with the idea to land an instrumented spacecraft on the surface. There ensued an unannounced and unconscious race to land on Mars, the result of which was a host of missions launched to the Red Planet in the years 1969–1975. The US launched two flyby spacecraft in 1969, Mariner 6 and Mariner 7, to follow up their 1965 flyby with better cameras and new instrumentation for determining the characteristics of the atmosphere. Both were successful. The USSR attempted to launch the first two of its new large spacecraft but both Proton boosters exploded. Almost 30 years were to pass before these missions were described in any detail (Perminov, 1999). The two spacecraft were orbiters intended to map the planet for landing sites and to obtain an accurate Mars ephemeris. The 1969 mission was also originally designed to deploy atmospheric probes from orbit to determine the properties of the atmosphere the USSR needed in order to design a soft lander for the following opportunity in 1971. The probes had to be deleted late in development due to mass problems with the spacecraft and insufficient time for testing (Perminov, 1999).

After the 1969 failures, the USSR proceeded with its plan to send soft landers to the planet in 1971. They were able to design an entry system based on measurements of the atmosphere by the Mariner 4, 6 and 7 missions published in the open literature and from ground-based telescopic observations. But the Americans were not willing to give them their unpublished Mars ephemeris, a requirement for accurately targeting an entry probe during approach to the planet. The lack of an accurate ephemeris drove the NPOL mission designers to attempt a very risky plan for 1971. They would launch an orbiter on a fast track to Mars to arrive much earlier than the heaver orbiter/lander missions. This spacecraft would beat the American orbiter missions to Mars and would obtain the required ephemeris to update the Soviet orbiter/lander missions while en route. An automated optical navigation system for the orbiter/landers was developed as a backup to this plan.

In 1971 the Americans attempted to launch their first Mars orbiter, Mariner 8, on May 9. The Centaur upper stage failed. A day later NPOL attempted to launch its fast-track orbiter. The Block-D upper stage also failed and stranded the spacecraft in Earth orbit. The opportunity to claim the first Mars orbiter was lost, but more importantly the navigational linchpin in the NPOL plan was lost. NPOL was forced to rely on its backup optical navigation system. This system was well ahead of its time and a tribute to the ingenuity of Soviet engineers, their skill in automation and the boldness with which they carried out their program, but it was an enormous untested risk at the time. The Americans would not attempt anything like it for decades, nor were they likely to have taken a similar risk. NPOL proceeded despite the loss of the orbiter, launching two orbiter/landers Mars 2 and Mars 3 later in the

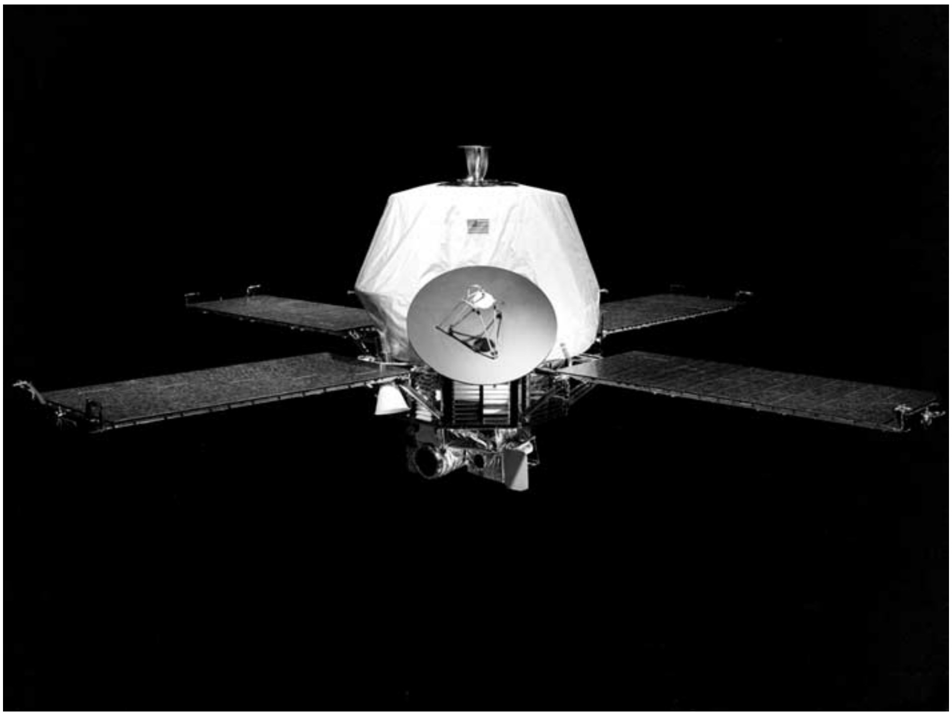

Figure 25. The Mariner 9 spacecraft.

month and placing its hopes on the backup autonomous optical navigation system. American hopes were revived when the Mariner 9 spacecraft was successfully launched at the end of May.

Mariner 9 (Figure 25) became the first successful planetary orbiter on November 14, 1971, and photographed the entire planet during almost one year of operations, revealing an entirely new planet unimagined from the much more limited data returned by the three previous flyby missions. Mars 2 arrived at the planet two weeks after Mariner 9. The autonomous optical navigation system performed as intended, sensing the position of Mars relative to the spacecraft, updating the guidance system for a mid-course maneuver to target the spacecraft for orbit insertion, carrying out the maneuver, and then updating the entry vehicle guidance system for its targeting maneuver post separation. As it turned out, Mars 2 was on a nearly perfect trajectory prior to the maneuver, a case not covered by the autonomous software, and entry targeting was fatally overcompensated. There had been insufficient time to test the software before launch. The carrier vehicle successfully slipped into an 18-hour elliptical orbit of Mars, but the entry vehicle entered the atmosphere at an overly steep angle and crashed. Nevertheless, Mars 2 became the first human-made object to impact Mars.

Mars 3 (Figure 26) arrived at the planet on December 2, 1971, and carried out its autonomous optical navigation sequence perfectly. The Mars 3 lander became the

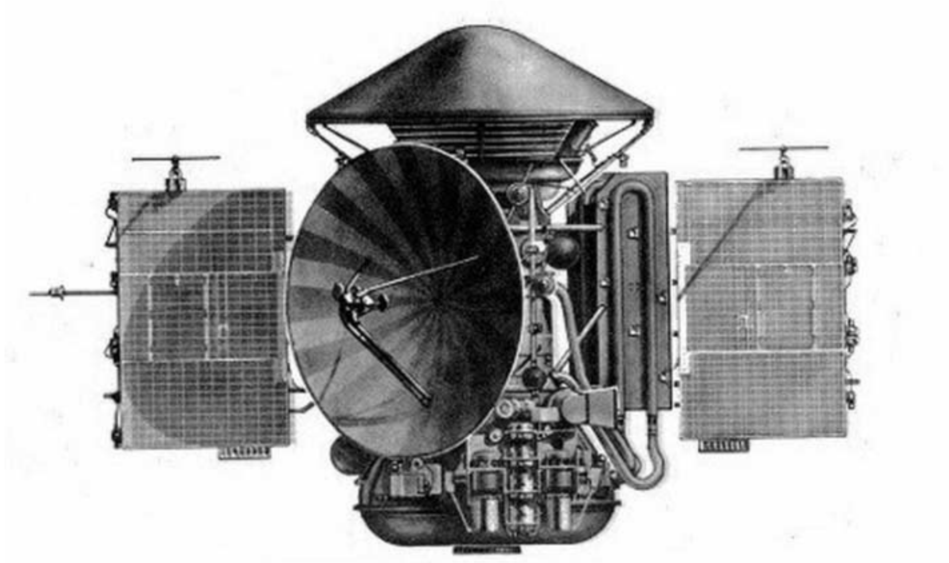

Figure 26. Drawing of the Mars 3 spacecraft.

first spacecraft to successfully land on the planet, but failed to return any useful data after it fell silent 20 seconds after sending a featureless image via relay from the orbiter. A truncated orbital insertion burn placed the Mars 3 orbiter in an extended 12.8-day orbit that compromised its science return. The Mars 2 orbiter data was also compromised by a poorly functioning communications system. Both orbiters returned data on Mars for 4 months.

The US skipped the following Mars opportunity in 1973 due to the extended development period required for its own orbiter/lander mission, Viking. Viking was to use the most powerful launcher in the US arsenal, the Titan-Centaur, and would be the most complex and technically challenging spacecraft in US history. The USSR took advantage of this hiatus in an attempt to beat Viking to the Martian surface. The energy requirements for the 1973 opportunity were too large for their 1971 orbiter/lander spacecraft, so the USSR assembled an armada of four spacecraft, two orbiters and two flyby/lander combinations. The orbiters were to carry out scientific measurements from orbit, but as in 1971 were also essential as communication relays for the landers. The flyby spacecraft carried a link to relay data from their deployed entry vehicles while on descent as well as an instrument package for remote sensing during the flyby.

All four spacecraft were successfully launched in July and August 1973. The Mars 4 orbiter flew past the planet after failing to conduct an orbit insertion burn, and returned only flyby images and radio occultation data. The Mars 5 orbiter arrived next and was placed into its planned orbit, but developed a fatal leak in the instrument compartment that ended the mission prematurely, leaving the Mars 6 and 7 landers yet to arrive without any communication relay capability from the surface.

Twelve days after Mars 5 fell silent the Mars 6 spacecraft, crippled by an almost useless communications system, arrived at the planet and carried out an autonomous targeting and deployment procedure for the entry system. The entry system performed perfectly and data was relayed through the flyby spacecraft from the lander system during parachute descent. Contact with the descent system was lost immediately prior to landing, probably when it hit the surface. Mars 6 was not heard from again, but was successful in making the first in situ measurements in the Martian atmosphere.

Perminov (1999) has published a revealing technical history of the Mars 2–7 missions at Mars. The scientific results have been summarized by Moroz (1978) and by Snyder and Moroz (1992). In spite of being the first to launch to Mars in 1960, in spite of eight launch attempts in the 1960s, and in spite of bold, innovative and massive efforts in 1969, 1971 and 1973, the Soviet Mars program suffered from terrible misfortune and was an immense disappointment. Only five of nine Soviet attempts in 1969–1973 had any scientific result. Exhausted after the all out campaign in 1973, the USSR abandoned Mars to the US Viking mission in 1975, which promised a lander with more capability than they could muster at the time.

The defining Mars missions of the decade, and for 20 years afterward, were the US Viking 1 and Viking 2 missions launched in summer 1975. Each spacecraft with its landers (Figures 27 and 28) reached the planet 10 months after launch and spent several months in orbit photographing the surface to certify a landing site. The entry systems were then deployed from orbit. Viking 1 became the first successful Mars lander on July 20, 1976, returning panoramic images from a dune and rock strewn wind-swept surface (see Figure 29 for an example). The Viking 2 lander followed on September 3. Primary communications from the landers were direct to Earth. Soon after landing, the landers measured the composition of the atmosphere and analyzed soil collected with an articulated scoop. The principal goal of the landers was to search for organic compounds and biologic activity at the microbial level in Martian soil. The life-detection instruments did have a reaction to the soil, but the consensus among the investigators was that the reaction was caused by an unusual oxidant in the soil. No organic material was detected and no compelling evidence was found for life. This result is not regarded as final evidence for the absence of life on Mars, but at the time it was a disappointment. The landers operated on the surface for many years, providing continuous meteorological monitoring, while the orbiters operated overhead carrying out an extensive photographic campaign mapping almost the entire planet. A Viking Orbiter mosaic is shown in Figure 30.

Almost all of the scientific results of the eleven missions to reach Mars between 1969 and 1976 came from the five American missions, with the single exception of solar wind interaction at Mars. The US results were extensive and revealing. Mariner 9 mapped 100% of the surface of Mars from orbit with a resolution of

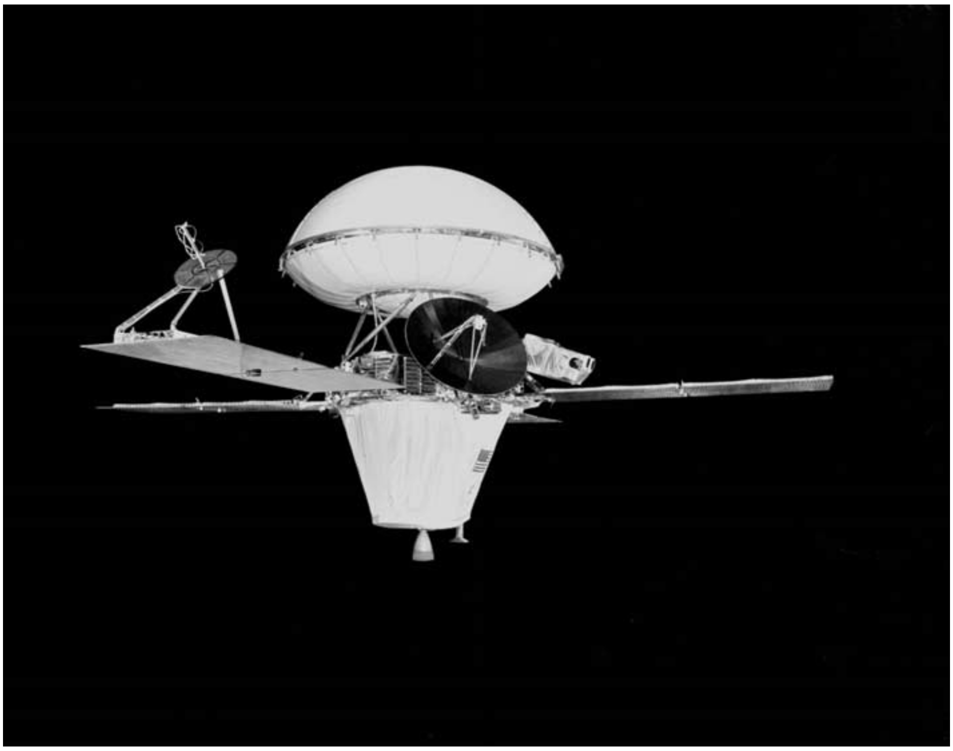

Figure 27. The Viking spacecraft.

about 1 km, and 1% of the surface at 100 m resolution. Giant mountains of volcanic origin were discovered including highlands, depressions, tectonic features, and sinuous valleys resembling dry beds of terrestrial rivers. The presence of many impact craters, as on Moon, was confirmed but these are the only common features between these two celestial bodies. There is no liquid water on the surface, but there were traces of hydrological processes such as terrestrial-like river valleys and evidence of permafrost. The Viking orbiters followed four years later to complete higher resolution mapping of a larger portion of the planet. The Viking 1 and 2 missions did not solve the question of life on Mars but they did deliver a great deal of detailed information on the planet itself. A host of papers dedicated to Viking data analysis remained current for 20 years after mission completion. A thick volume (Kieffer *et al.*, 1992) was compiled with reviews summarizing the science from Viking and other missions.

The Viking missions occupied the pinnacle of the first era in Mars exploration, which lasted from 1960 until 1976. There seemed nothing else to do after having finally landed on the planet and found it to be dry, cold, rocky, and with no evidence for life. Mars was forgotten for another 12 years. Its continued exploration was revived by the USSR, which after so many successes at Venus and in the absence of any apparent serious interest from the Americans, decided to try again at Mars.

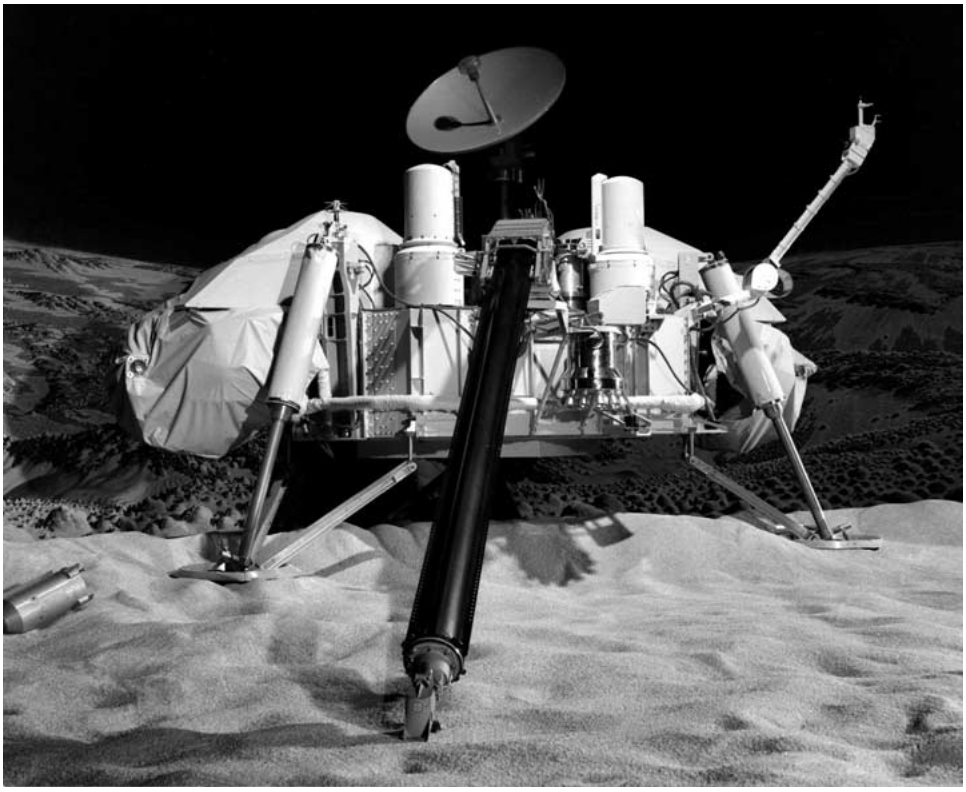

Figure 28. The Viking lander in a display ‘sandbox’.

The USSR had developed an advantage over the Americans with a much larger and more capable spacecraft and a foothold on international leadership after the Vega 1 and 2 missions. The primary objective would be close encounters with Phobos to deliver small landers and to conduct active and passive remote sensing of its surface. The secondary objective was advanced remote sensing of Mars from orbit including surface mapping in the thermal IR range, mineralogical spectral mapping in the near IR, and solar occultation limb sounding of the atmosphere. Instruments were also carried for studies of the plasma environment. A very complex and comprehensive payload comprised of a large number of scientific instruments was built through international cooperation. A new spacecraft design was developed, replacing the venerable Venera/Mars design and intended to be used for other Soviet planetary missions in the future.

Two of these spacecraft were launched in July 1988. Phobos 1 was lost during cruise due to an error in a command sequence sent from Earth to the spacecraft. Phobos 2 arrived at Mars in January 1989 and was inserted safely in orbit. The orbit was corrected several times and a final orbit achieved close to that of Phobos from which remote sensing studies were conducted of both Mars and the satellite. A final

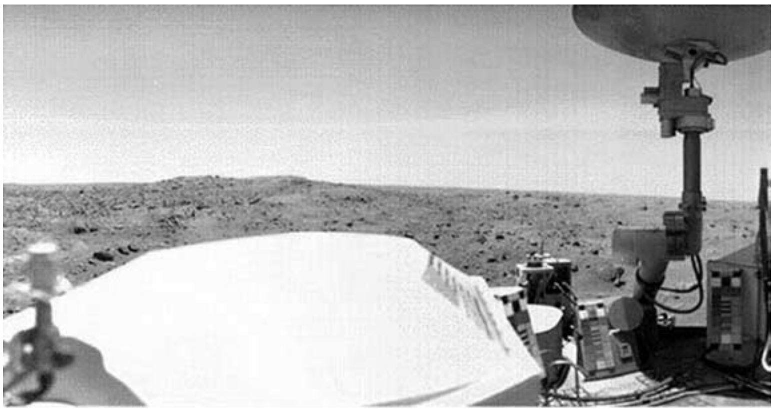

Figure 29. Image across the Viking 1 lander on the surface.

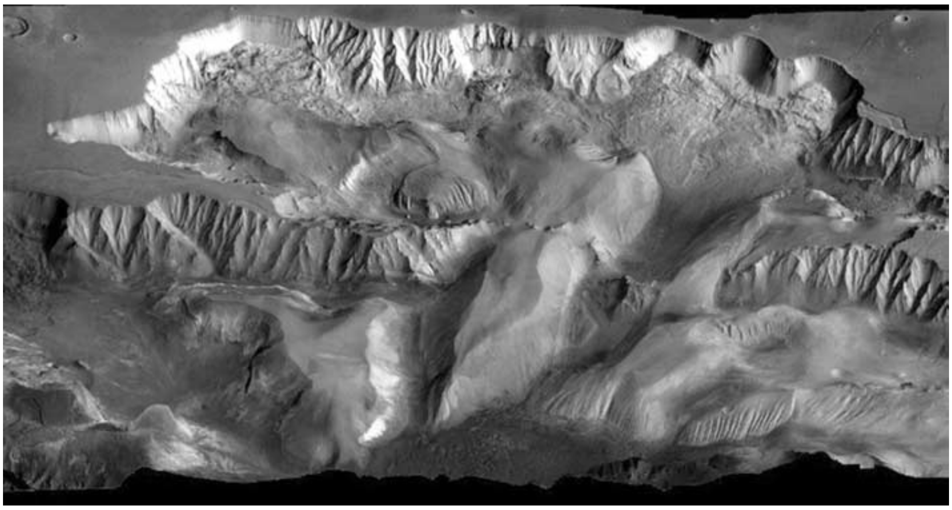

Figure 30. Image mosaic of Candor Chasma from Viking Orbiter 2.

operation was planned for a very close passage above the surface of the satellite to deploy two small stations to land on Phobos and to conduct active remote sensing from the spacecraft. However on 27 March 1989, the day before the encounter, the spacecraft was lost due to a failure of the on-board control electronics. While the Phobos mission may not have succeeded in meeting its ultimate goals, the science output from the Phobos 2 spacecraft far exceeds that obtained by all previous Soviet Mars missions. An example of the unique thermal imaging provided by Phobos 2 for the first time is shown in Figure 31.

The loss of Phobos 2 resulted in a heated debate in the USSR over the next step in planetary exploration. Some argued to make another attempt at the same mission while another faction wanted to develop a different mission focused primarily on Mars rather than Phobos. The latter opinion prevailed and a typically ambi-

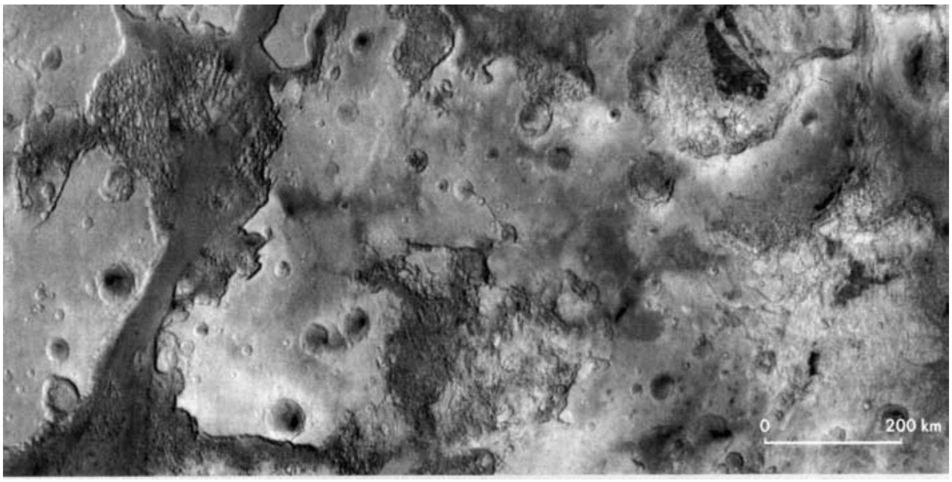

Figure 31. Phobos 2 Termoscan infrared image of Ares Vallis outflow channel and adjacent regions: the 'source' region of the large dry outflow channels Simud Vallis, Tiu Vallis and Ares Vallis – from left to right.

tious new project developed consisting of five flight elements: an orbiter, small landers ('small stations'), penetrators, a rover ('Marsokhod'), and a Mars balloon. Twenty countries were solicited to participate in the development of the science instruments and investigations including the USA. The name of the project was originally Mars 94 for a launch in 1994, but renamed Mars 96 when postponed to 1996 due to the complexities of not just spacecraft and instrument development but also to complexities of national politics and financing. The project was started in one state – the USSR – but continued and completed in quite another – The Russian Federation.

In the meantime, the Americans had responded to the Soviet turn to Mars in the mid-1980s with their own orbiter mission, Mars Observer. This was a very modest spacecraft relative to the Soviet Phobos and Mars 96 spacecraft, and intended to be the first of a new low cost series of planetary 'Observer' spacecraft. Also originally intended for launch in 1990, and then postponed to 1992, Mars Observer development costs escalated – effectively aborting any idea of continuing the series. It was launched in 1992 and flew successfully to Mars until 3 days prior to orbit insertion, when the propulsion system failed catastrophically and for the first time ever an American planetary spacecraft had failed after a successful launch.

Now it was once again the USSR's turn, but by this time the country had become Russia after the demise of the Soviet Union in 1991. The Russian Space Agency was created in 1992 and the inherited Mars 96 mission became its most important scientific project. For technical development and financial reasons the new space agency descoped the project by canceling the balloon and rover after a suggestion by V. M. Kovtunenko. The Russian economy and its industry continued to devolve during the radical change from a planned to a capital economy, and financial support for Mars 96 continued to fail. Resources and subsystems were not delivered on schedule. The dual launch policy was abandoned and the second spacecraft canceled.

Finally in November 1996 a single Mars 96 spacecraft was launched, but failed when the second burn of the fourth stage went awry and the spacecraft re-entered the atmosphere. The failure assumed significance vastly different in the new Russia than in all previous Soviet experience. The failure happened in the open instead of in secrecy, and with a large number of international partners involved. There was no backup launch planned, and the failure was probably the result of insufficient resources when all previous flight projects could count on far higher levels of investment and the use of expensive launchers. This single failure signaled the end of Russian investment in scientific planetary exploration missions at the end of the 20th Century, after the Soviet Union had tolerated dozens of successive failures earlier in the space age.

The American response to their loss of Mars Observer was quite the opposite. They immediately developed not just a replacement mission but instead a whole program of new missions to explore Mars. This new line of missions was called the 'Mars Surveyor Program'. It was based on the idea of distributing mission risk among a number of small missions instead of risking everything on one complex mission. The Surveyor program provided for the launch of two low-cost spacecraft on less expensive Delta II launchers in each Mars opportunity, maximizing the probability of at least one success per launch opportunity. The original Mars Observer science objectives were retained and a rebuilt payload distributed over three small orbiters to be launched in successive opportunities. One orbiter and one lander were to be launched in each opportunity.

The first two of these new spacecraft were launched in 1996 – Mars Global Surveyor and Mars Pathfinder. Their combined cost was far less than Mars Observer and both were extraordinarily successful. The Mars Global Surveyor orbiter was launched in early November 1996, 9 days before Mars 96, and entered Mars orbit in September 1997. It was the first spacecraft to rely on aerobraking for achieving a close, circular mapping orbit. The spacecraft returned extensive high-resolution surface imagery, thermal IR spectral imagery, laser altimeter topography, gravity field, magnetic field data and continues operations in orbit today. One of thousands of images obtained by MGS orbiter is presented in Figure 32.

The Mars Pathfinder mission was launched in early December 1996 and landed successfully on July 4, 1997. It was the first use of airbags for terminal shock dissipation by the Americans, who adapted the technique from early Soviet landers such as Luna 9. The lander deployed the first Mars rover, Sojourner, a six-wheeled micro-rover that operated for almost three months in the lander vicinity measuring the elemental composition of soil and rocks (Figures 33 and 34).

Encouraged by their success with this new 'faster, better, cheaper' strategy, the Americans developed two new spacecraft for the 1998 launch opportunity. These were even less expensive than the 1996 spacecraft, and in fact too inexpensive

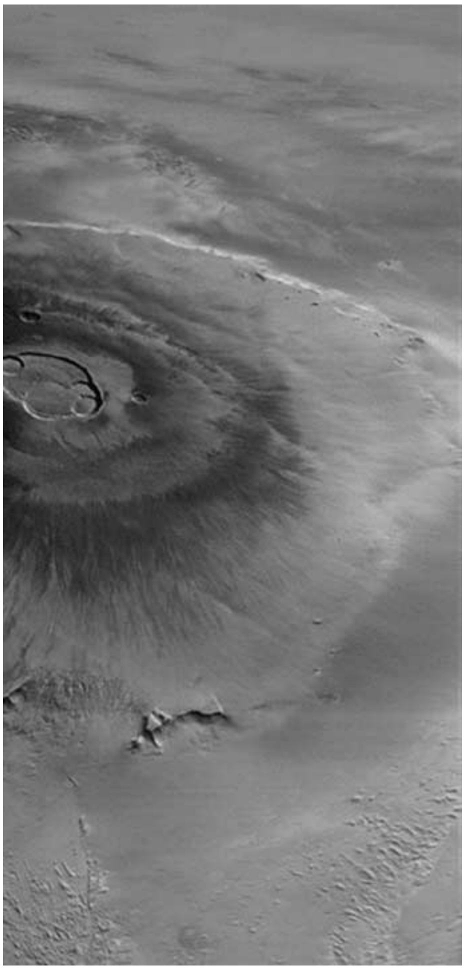

Figure 32. Oblique image of Olympus Mons from Mars Global Surveyor.

as it turned out. Both were launched and flew successfully to the planet without incident, but both failed at their target. The Mars Climate Orbiter was lost in September 1999 when the spacecraft flew too low into the atmosphere during the orbit insertion maneuver. This embarrassing navigational error was very atypical of the Americans. Three months later the Mars Polar Lander was lost along with two experimental Deep Space 2 penetrators when all three disappeared after separation from the carrier spacecraft just prior to entry. Post-mission analysis of these two failures revealed deficiencies in navigation and engineering caused by insufficient resources. The US had pushed the 'faster, better, cheaper' philosophy beyond its limits and would have to retreat, forcing a new architecture for their future Mars exploration program.

Figure 33. The Sojourner rover.

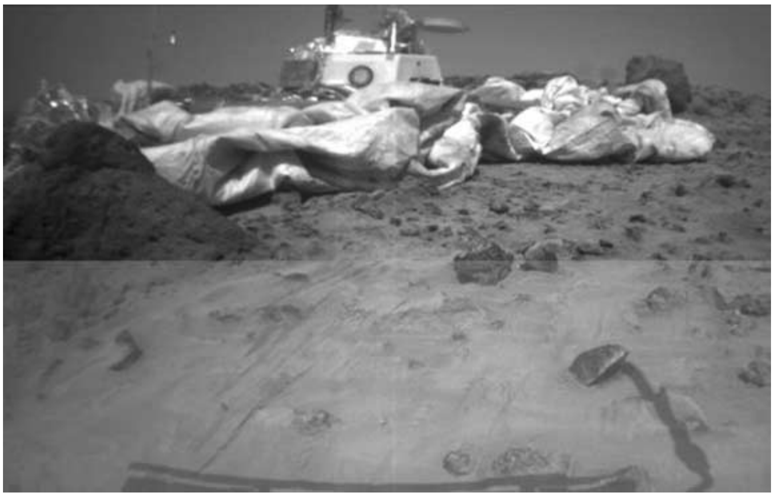

Figure 34. The Mars Pathfinder lander imaged from the rover.

Unlike the first three decades of the space program, the decade of the 1990s was not overly kind to the US in Mars exploration. It lost three of five missions launched to the planet – all lost at the planet during the terminal phases of their approach. Nonetheless, its two successful missions were spectacular and set the stage for a new era in less expensive but scientifically rewarding missions to the planet. The discoveries by these missions have renewed interest in Mars exploration around the world. The American program continues into the 21st Century and other countries have joined the enterprise including France and Italy. ESA is preparing the Mars Express mission for launch in 2003 with its small Beagle 2 lander, and Japan launched its first Mars mission in 1998, Nozomi, scheduled to arrive in December 2003.

The results of planetary missions sent to Mars changed our science fiction-driven preconceptions of a planet crawling with life, whether belligerent or intelligent canal-builders, to the very different planet we know it is today. Mars slides around the Sun just at the limit of the habitability zone around our home star. It appears to have had a lot of water flowing on its surface in its ancient past, perhaps even a northern ocean for a time, and a long history of climate change with perhaps warmer and wetter conditions in its past, but today it is cold, dry and inhospitable. The atmosphere is mainly carbon dioxide, a few percent nitrogen and argon, with only trace amounts of oxygen and water vapor, and a pressure more than a hundred times less than at Earth. The solar ultraviolet flux is almost unattenuated at the surface, the surface temperature barely reaches freezing on a bright summer day at the equator and there is no liquid water. It has extensive and even global dust storms with strong local winds and dust devils. There is no sign of life on its volcanic, rock-strewn surface. There are ample signs of subsurface ice, perhaps even liquid water at some depth below the surface, and it remains possible that if life ever started on Mars that microscopic life may still survive at these depths.

As inhospitable as it is, Mars remains the planet most like Earth in its surface conditions, and so humans continue to hold out hope for its past and even future habitability. The planet is tilted to the ecliptic by nearly the same amount as the Earth and has a day only very slightly longer. It has polar water ice caps that wax and wane with the seasons. It has many of the same tectonic features we are familiar with on Earth including extremely large volcanic constructs and deep, wide valleys. Mars will continue to be an intense object of exploration well into the current century.

7. Missions to the Outer Planets

Table IV lists events in exploration of the Outer Planets chronologically. The US is the only country to have sent spacecraft to the outer planets. All were launched successfully, and there were no in-flight failures in spite of the very long duration of the missions. These are very difficult technical missions requiring long-lived, radiation-hard electronics for the avionics, radioisotope thermal generators for power, and reliable long-duration propulsion systems. It was a daunting challenge in the late 1960s to contemplate sending spacecraft through and beyond the asteroid belt into deep cold soak of the outer solar system. The distances were enormous, 2–15 times farther than from Earth to Mars, and the flight times measured in many years instead of many months.

The outer solar system is the realm of the giant planets, Jupiter king among them, and while they were the dominant bodies in the Solar System, very little was known about them. They were known to have deep atmospheres containing

TABLE IV
Missions to the Outer Planets in the 20th century

1972

Pioneer 10 Jupiter Flyby USA 2 Mar 1972 Atlas-Centaur

The first flight to an outer planet successfully navigated the asteroid belt and flew past Jupiter on 4 Dec 1973 at distance of 132 250 km. Pioneer 10 returned 500 images of Jupiter and its moons, collected data on Jupiter's magnetic field, trapped charged particles and solar wind, and paved the way for the spacecraft which followed by providing important environmental data in the asteroid belt and at the Jupiter system. Crossed the orbit of Pluto on June 13, 1983 (Fimmel et al., 1977).

1973

Pioneer 11 Outer Planets Multiple Flyby USA 5 Apr 1973 Atlas-Centaur

Jupiter flyby 3 Dec 1974

Followed Pioneer 10 and flew past Jupiter on 4 Dec 1974 at a much closer distance of 42 900 km. Pioneer 11 repeated the measurements of Pioneer 10 on a different trajectory through the Jupiter system and was given a gravity assist to fling it across the entire Solar System to encounter Saturn on 1 Sep 1979.

Saturn flyby 1 Sep 1979

The first spacecraft to fly past Saturn, passing the outer edge of Saturn's A ring at a distance of 3500 km, and traveling underneath the ring system to pass Saturn itself at a distance of 20 930 km. Pioneer 11 repeated imaging and in-situ radiation and magnetic field measurements it conducted at Jupiter (Fimmel et al., 1977).

1977

Voyager 2 Outer Planets Multiple Flyby USA 20 Aug 1977 Titan 3E Centaur

Launched first on a lower energy trajectory to fly past all four major outer planets, Voyager 2 was the second to reach Jupiter and Saturn but continued on to conduct the first flybys of Uranus and Neptune.

Jupiter system flythrough 9 Jul 1979

Confirmed discoveries of Voyager 1 and obtained additional data on the atmosphere and Galilean satellites.

Saturn system flythrough 25 Aug 1981

Confirmed the discoveries of Voyager 1.

Uranus system flythrough 24 Jan 1986

Obtained additional detail on the rings, and imaged the icy satellites. Found Miranda's surface to be a jumble as if a reconstructed satellite. Uranus lacks visual evidence of an atmospheric circulation system, presents a bland appearance and shows no evidence of an internal heat source like the other three giant planets.

Neptune system flythrough 25 Aug 1989

Found a blue, rapidly circulating atmosphere with dynamically changing white clouds and a few large dark lenticular spots. A close flyby of Triton revealed an unusual surface and a thin, cold atmosphere with dark geysers and icy volcanism probably involving nitrogen and hydrocarbons. The rings were shown to be longitudinally non-uniform (Voyager 2, 1980).

TABLE IV
Continued

Voyager 1	Outer Planets Multiple Flyby	USA	5 Sep 1977	Titan 3E Centaur
Second to be launched. With success of the first launch of Voyager 2 on a four-planet tour, Voyager 1 was sent on a faster trajectory targeted specifically for a close flyby of Titan at Saturn and sacrificing any subsequent planetary encounters.				
	Jupiter system flythrough		5 Mar 1979	
Discovered the widely varied nature of the Galilean moons, the intense volcanism of Io, the fractured icy surface of Europa, the tortured surface of Ganymede and the crater-battered surface of Callisto. Found Europa, Ganymede and Callisto to be icy bodies with low bulk density. Discovered Jupiter's ring and small inner moons. Obtained close-up multi-color imagery of the Jovian clouds and examined the dynamics of the Red Spot and cloud bands. Found lightning on the dark side.				
	Saturn system flythrough		12 Nov 1980	
Discovered complex structure of the Saturnian rings, transient radial spokes, sheparding satellites, and the dusty debris nature of the extended ring plane of Saturn. Imaged Saturn's icy Moons. Flew close by Titan and discovered a heavy, extended nitrogen atmosphere containing methane, hydrocarbons, complex organic molecules and a thick, permanent haze layer (Voyager 1, 1979).				
1989				
Galileo	Jupiter Orbiter/Probe	USA	18 Oct 1989	Shuttle-IUS
First orbiter of Jupiter and first Jupiter atmospheric probe. The probe was released on 13 July 1995 and successfully descended into the Jovian atmosphere on 7 December 1996 while the in-bound orbiter relayed data to Earth. Orbiter subsequently placed in Jovian orbit on the same day. The probe measured the structure, optical properties and composition of the atmosphere. The orbiter carried out multiple close flybys of the four Galilean satellites and examined the dynamics of the Great Red Spot and other storms on Jupiter. Discovered the potential for subsurface liquid water at Callisto, Ganymede and ice-covered Europa.				
1997				
Cassini-Huygens	Saturn Orbiter/Titan Probe	USA	15 Oct 1997	Titan 4B Centaur
Joint NASA-ESA mission. The Titan probe was built by ESA, the Saturn orbiter by NASA. Conducted two flybys of Venus and one flyby of Earth enroute to Saturn. Conducted joint science operations with Galileo during gravity assist flyby of Jupiter on 31 December 2000. Saturn orbit insertion scheduled for 1 July 2004. Saturn system tour will use Titan passes on each orbit to redefine the orbit. The Titan probe will be deployed on the third orbit for a three-hour descent in the atmosphere to the surface. Goals include scientific exploration of the planet, its atmosphere, rings and magnetosphere, Titan and the icy satellites.				

Figure 35. Artists drawing of the Pioneer 10 spacecraft at Jupiter.

mainly hydrogen with minor amounts of the hydrides of carbon (CH_4) and nitrogen (NH_3). Jupiter was known to have gigantic storms, a strong magnetic field and a large radiation belt. The Galilean satellites were mere points of light in a telescope. It was known that Titan had an atmosphere with methane in it, but all else was speculation. The nature and longevity of Saturn's rings were unknown. The rings of Uranus and Neptune had not yet been discovered. And Pluto was a pinpoint of light so far away that virtually nothing was known other than its orbit, including its mass and diameter (once thought to be the size of Earth!).

Pioneers 10 and 11 were launched in 1972 and 1973, respectively, to become the first missions to cross the asteroid belt and examine the environments of Jupiter and Saturn. These spacecraft were aptly named because their main purpose was to scout the trail between Earth and the Outer Planets, and determine the hazards that might be presented to more capable spacecraft that were planned to follow. It was not known at the time if the asteroid belt was safe to navigate, so the spacecraft carried instruments to measure the micrometeorite flux in the asteroid belt. They also carried instruments to determine the radiation flux at Jupiter and the properties of Jupiter's magnetic field and its interaction with the solar wind. The Pioneer series were spin-stabilized spacecraft and therefore did not carry cameras, but Pioneers 10 and 11 did carry a scanning photometer from which low-resolution images could be constructed.

Pioneer 10 (Figure 35) was launched in March 1972 and flew successfully through the asteroid belt, proving that the asteroid belt posed no barrier to spacecraft travel, and then past Jupiter 21 months after launch at an encounter distance of less than two Jupiter radii above the cloud tops, a distance deemed likely to be safe for a first encounter with a large but uncharacterized set of radiation belts.

The spacecraft survived the encounter and returned invaluable data on the planet including measurements of the magnetosphere, solar wind interaction and radiation belts, weather patterns on the planet, heat balance within the planet, and the hydrogen/helium ratio in the atmosphere.

Pioneer 11 was launched 13 months after Pioneer 10 and flew past the planet exactly one year after Pioneer 10. It was targeted much closer to the planet, a little more than half a Jovian radius above the clouds, on a near-polar trajectory to fling the spacecraft across the entire Solar System to encounter Saturn almost five years later. Pioneer 11 became the first spacecraft to fly past Saturn on September 1, 1979, passing just outside the edge of the rings and underneath the ring plane repeating the measurements it had made at Jupiter. Pioneer 11 proved it safe to fly close to the rings, discovered the outer F-ring, and imaged the rings in more detail than seen from Earth including from behind the planet.

The two Pioneer spacecraft cleared the path for the more capable Voyager spacecraft that followed later in the decade. A unique celestial navigation opportunity arose in the second half of the 1970s when it became possible to visit all four giant planets in series with a single spacecraft ('The Grand Tour'). This opportunity occurs in only three consecutive launch years every 176 years, and 1977 was a just such a fortuitous year precisely when the US planetary exploration program was most ready for it. The Voyager spacecraft were 3-axis stabilized in the Mariner tradition with cameras, a comprehensive science payload, and a very capable X-band communication system using a large parabolic antenna.

Voyager 2 (Figure 36) was launched first on a longer, slower trajectory than Voyager 1 in order to preserve the option to proceed from Saturn outward to Uranus and Neptune. Voyager 1 was launched later on a trajectory that would allow a close encounter of Titan at Saturn. The Voyager missions were epic, passing through four systems containing a central giant planet with a retinue of rings and icy moons. The Voyagers obtained highly resolved images of the atmospheres of these planets, of their ring systems, and of their large satellites. The Voyager missions demonstrated that the Solar System is not dull, that every planet and every moon is different than the other, and that the largest moons of the outer planets are worlds in themselves each having its own particular call for exploration. Figures 37 and 38 show some results of the Voyager 2 imaging experiment at Saturn and Neptune.

Although second to be launched, Voyager 1 reached Jupiter first in March 1979 and discovered the varied nature of the Galilean satellites including the intense volcanism at Io and the cracked, icy surface of Europa. Jupiter's ring was discovered along with its attendant small moons. Intricate details of Jupiter's cloud bands and cyclonic storms were imaged. Eight months later the spacecraft encountered Saturn and discovered the complex structure of the rings, spokes and shepherding moonlets. The close flyby of Titan revealed a small planet in orbit about Saturn enshrouded in a perpetual red-orange cloud cover in a thick, extended nitrogen atmosphere containing methane and trace organic compounds. The smaller icy

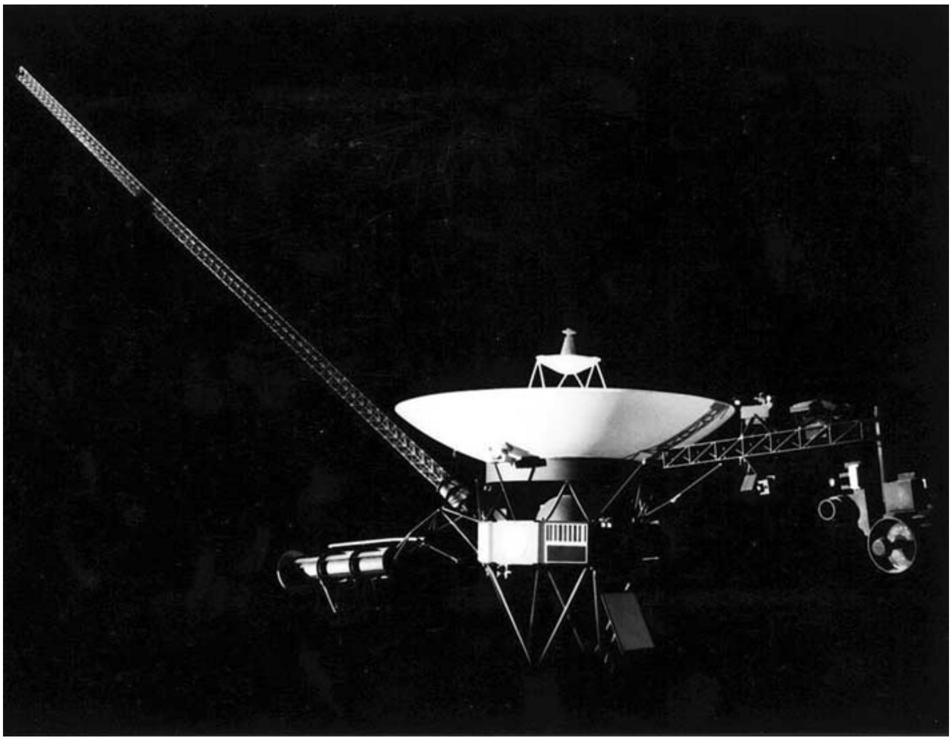

Figure 36. The Voyager spacecraft.

moons of Saturn were shown to have very individual surfaces shaped in some cases by tectonic processes.

Voyager 2 followed at Jupiter and Saturn by several months. It was the first spacecraft to reach Uranus on January 24, 1986, and found the planet to be very bland in appearance and lacking an internal heat source like the other three giant planets. Uranus' rings were imaged in detail including its icy satellites. Miranda's surface was found to be particularly interesting, jumbled very noticeably as if it had been disrupted and reassembled. The epic tour was completed with a flyby of Neptune on August 25, 1989. Voyager 2 found Neptune with a deep blue atmosphere containing high white methane clouds and large lenticular dark spots tracing the circulation. The rings were found to be longitudinally non-uniform. Voyager 2 made a close pass of Neptune's large satellite, Triton, which was found to have a thin atmosphere with unusual surface markings and dark geysers probably of nitrogen and hydrocarbon material.

All four of these early missions to the outer planets are now on their way out of the Solar System as a result of the energy gained in their flybys of these huge planets. The Voyagers remain in contact and it is hoped that their passage through the heliopause will be recorded before their power sources deteriorate sometime in the next 20 years. The results of the Pioneer and Voyager missions have been summar-

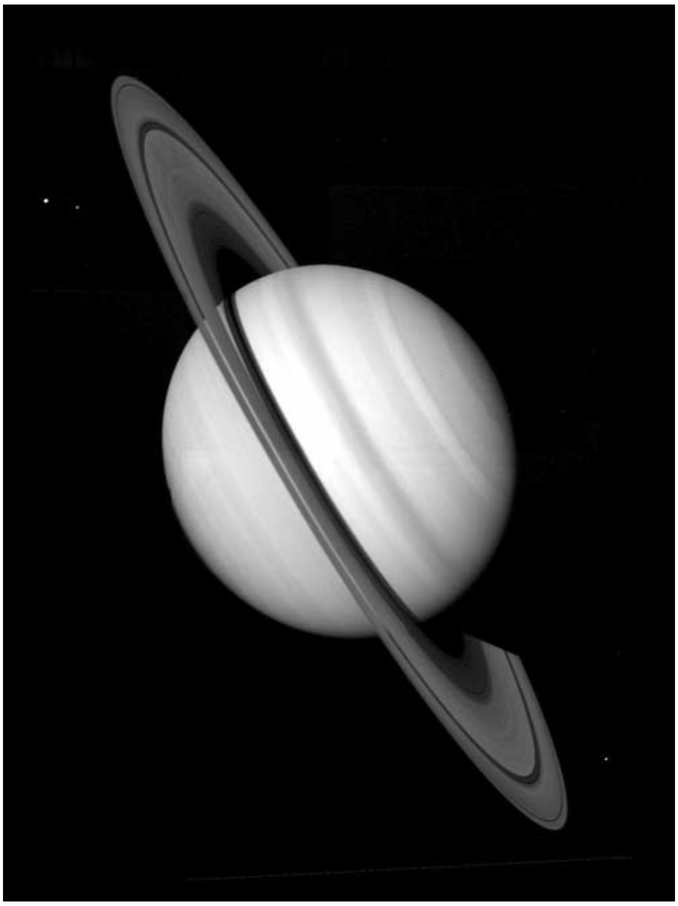

Figure 37. Saturn from Voyager 2.

ized in many publications (Gehrels, 1974; Morrison, 1982; Gehrels and Matthews, 1982; Greenberg and Brahic, 1984; Burns and Matthews, 1986; Bergstrahl *et al.*, 1991; Cruikshank, 1995).

After successful flyby reconnaissance, the next step in the exploration of the outer planets is to conduct orbital surveys of the planet, its rings and satellite systems. In 1989, the Galileo Jupiter orbiter/probe mission was launched to Jupiter and development of the Cassini-Huygens Saturn orbiter and Titan probe mission was approved. Galileo carried a German-built propulsion system and science instrument. Cassini-Huygens is a joint project with ESA, with the orbiter built in the US and the Titan probe built by ESA. Both spacecraft were heavily loaded with fuel for orbit insertion and carried complex, comprehensive science payloads. Because of their large mass, the mission design required use of the largest launch vehicles available and gravitational assists from Venus and Earth in order to exit the inner solar system and reach their targets.

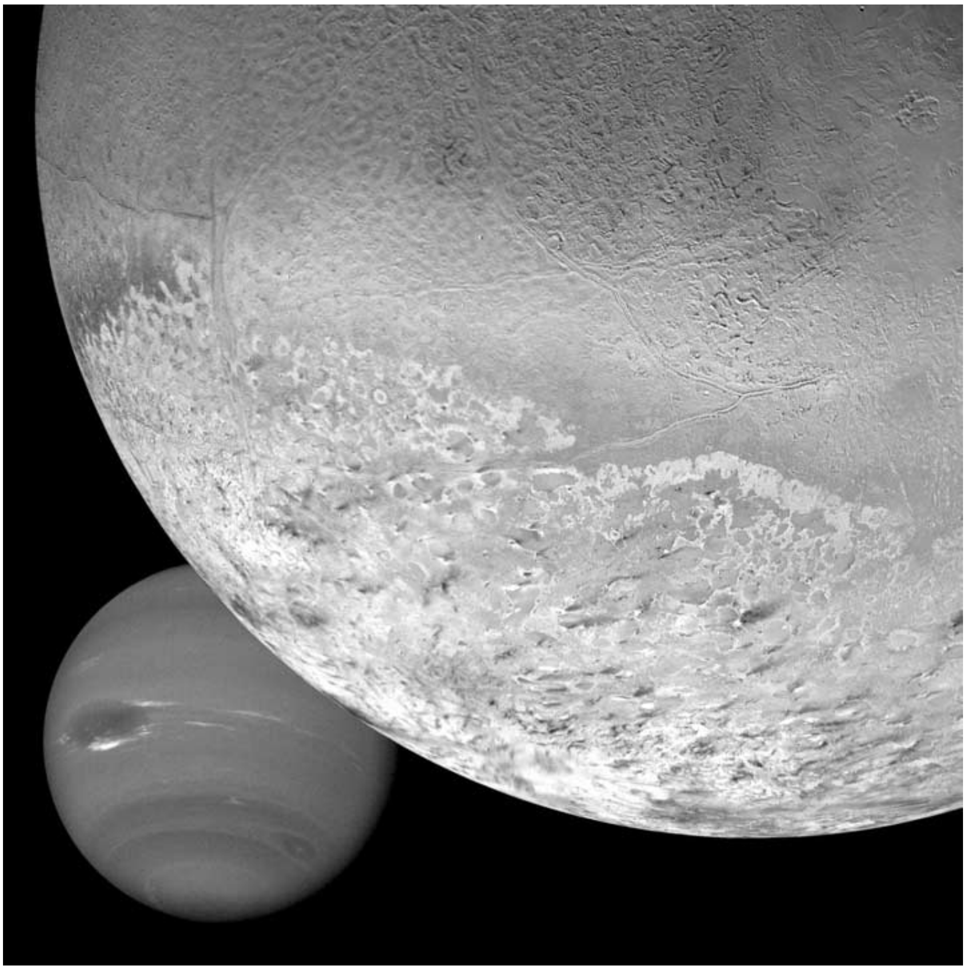

Figure 38. Montage of Neptune and Triton images from Voyager 2.

The Galileo spacecraft design was unique, a 3-axis stabilized spacecraft with a spinning portion for the plasma measurement devices and a deployable mesh high-gain antenna. This antenna failed to deploy properly during cruise to Jupiter rendering it useless, and it is a tribute to the skill of the Galileo team that this project became such a success after such a debilitating failure. It was launched from the Space Shuttle attached to an IUS (Interim Upper Stage) for injection on an interplanetary trajectory. Galileo made a pass at Venus and then two passes at Earth before crossing the asteroid belt for Jupiter. In between the Earth flybys, Galileo flew past the main belt asteroid Gaspra, and on its passage through the asteroid belt the spacecraft flew past the asteroid Ida, discovering its small moon. During the last part of its cruise to Jupiter, Galileo observed the impact of Comet Shoemaker-Levy with the planet. One of the many fantastic Galileo images is presented in Figure 39.

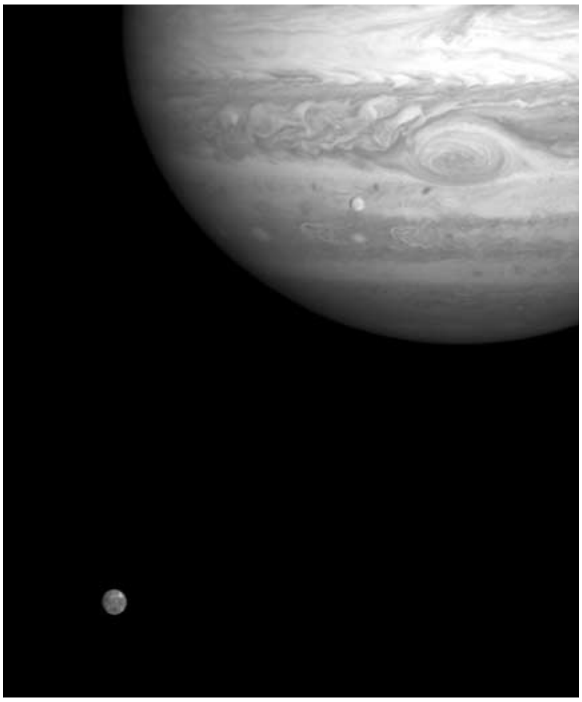

Figure 39. Galileo image of Jupiter with Ganymede in the foreground and Europa superposed on the planet.

Galileo released its atmospheric probe almost five months before arrival, which flew silently in tandem with the orbiter. Its signal was picked up and recorded by the approaching orbiter on December 7, 1996, as the probe successfully descended into the atmosphere and finally disappeared at a depth near 20 bars. Galileo then conducted a successful orbit insertion burn and has been orbiting Jupiter ever since, conducting a close flyby of one of the Galilean satellites on almost every orbit about the planet. It has found compelling evidence of an ocean below the icy surface of Europa and evidence of liquid water layers in Callisto and Ganymede as well. The orbiter has examined the dynamics of the giant storms on Jupiter and the probe determined the structure, optical properties and composition of the atmosphere.

Cassini-Huygens, the heaviest and most complex planetary spacecraft ever built by the US, was launched in October 1997 on a Titan 4B Centaur, the most powerful vehicle in the US inventory. The spacecraft conducted two flybys of Venus and one of Earth to reach sufficient velocity for flight to Jupiter. At Jupiter the flyby trajectory added sufficient energy to enable the spacecraft to reach Saturn. During the Jupiter flyby, Cassini-Huygens conducted joint science operations with Galileo. Cassini-Huygens is scheduled to reach Saturn on July 1, 2004, for a 4-year tour during which it will fly past Titan on each orbit to retarget the spacecraft to another part of the Saturn system. The Huygens Titan probe will be released during the third orbit for a three-hour descent through the atmosphere to the surface. The probe may survive the landing and carries a surface science package for this contingency.

It is a remarkable fact that at the end of the 20th Century, and after less than 50 years of development, planetary spacecraft have been dispatched to explore vast reaches of the Solar System from Mercury to Neptune and beyond. Every planet in the Solar System has been visited by at least one spacecraft except distant Pluto. Three of these planets have been extensively explored with orbiters and probes or landers. The saga of the Voyager mission throughout the outer solar system, exposing the existence of so many varied and remarkable worlds, will remain one of the highlights of this story. These half dozen outer planet spacecraft (one yet to reach its target) have produced an immense quantity of information on a wholly different solar system existing on the other side of the asteroid belt.

8. Missions to Small Bodies of the Solar System

Table V lists events in exploration of asteroids and comets chronologically. Small bodies such as asteroids, comets, and small natural satellites are of special interest to understanding the origin and early evolution of the Solar system. Many, such as new comets, may be composed of the original material out of which the Solar System was made. Others may provide clues to chemical processing within the early solar nebula, and still others may contain evidence of physical and chemical processes within small planets subsequently blasted apart by collisions in the area of the present day asteroid belt. The early Solar System was a swarm of small bodies, and most of those within the planetary zone were lost by collision with the accreting planets in the first billion years of Solar System history. The remaining small bodies have a history to tell of the origin and evolution of our home planetary system.

The first small bodies to be explored were comets, and the first of these was Giaccobini-Zinner. The International Comet Explorer (ICE) was launched initially in 1978 as ISEE-3 to examine interplanetary plasma. It was renamed and re-targeted to G-Z in 1983 and accomplished a far flyby in 1985. The payload was not optimized for comet exploration and the scientific results were minimal. The redirection of ISEE-3 was a reaction in the US to failure to approve a mission to Comet Halley while the Europeans, Japanese and USSR all mounted missions for this historic opportunity.

Comet Halley has an orbital period of 76 years. In its previous apparition in 1910 the perihelion passage had been in close proximity to the Earth and provided a spectacular view, but in 1986 Halley's perihelion was on the opposite side of the Sun and a good view would require exploration by spacecraft. All of the space-faring nations of the time, except the US, developed missions to explore this famous comet. The flight and observation plans of these missions were coordinated through a new international organization, the Inter Agency Consultative Group (IACG).

TABLE V

Missions to Small Bodies in the 20th century

1978					
ICE	Giaccobini-Zinner	flyby	USA	12 Aug 1978	Delta
International Comet Explorer. Originally launched as a space physics mission, ISEE-3, the spacecraft was renamed and redirected to Comet Giaccobini-Zinner in 1983. Conducted the first comet flyby through the far tail of G-Z on 11 Sept 1985.					
1984					
Vega 1	Halley	flyby	USSR	15 Dec 1984	Proton-D
After completing its mission at Venus in June 1985, spacecraft bus continued on to fly by Comet Halley through its coma at 8890 km distance on 6 Mar 1986. Returned images of the nucleus and internal coma structure throughout a set of phase angles. Conducted plasma science, dust flux measurements, and dust and gas composition analyses (Sagdeev et al., 1986; Grewing et al., 1987; Reinhardt, 1986: Vega 1 and 2, 1987: Vega and Giotto, 1986).					
Vega 2	Halley	flyby	USSR	21 Dec 1984	Proton-D
Same design and science as Vega 1. Spacecraft flew by Comet Halley at 8030 km distance on 9 Mar 1986. Both Vega 1 and Vega 2 preceded the European Giotto spacecraft to provide better ephemeris data on Halley for Giotto's much closer and riskier flyby. Carried international instruments (Sagdeev et al., 1986; Grewing et al., 1987; Reinhardt, 1986: Vega 1 and 2, 1987: Vega and Giotto, 1986).					
1985					
Sakigake	Halley	flyby	Japan (ISAS)	7 Jan 1985	M3S2
Conducted a very distant 6 990 000 km flyby of Comet Halley on 11 Mar 1986. Conducted charged particles and magnetic fields measurements (Grewing et al., 1987; Reinhardt, 1986).					
Suisei	Halley	flyby	Japan (ISAS)	18 Aug 1985	M3S2
Conducted a distant 151 000 km flyby of Comet Halley on 8 Mar 1986. Conducted Lyman-alpha imaging of the hydrogen corona and charged particles measurements (Grewing et al., 1987; Reinhardt, 1986).					
Giotto	Halley	flyby	Europe (ESA)	2 Jul 1985	Ariane-1
The first European planetary spacecraft conducted a very close 596 km flyby through the coma of Comet Halley and returned images of the nucleus and internal coma structure with better resolution than Vega.					
	Halley	flyby		14 Mar 1986	
	G-K	flyby		10 Jul 1992	
Conducted particles and field measurements, dust flux, size and composition, and gas composition. Giotto suffered some damage from coma particle impacts but survived for a second encounter with another comet. Flew by Grigg-Skjellerup at close distance on 10 Jul. 1992, but without imaging because of damage to the camera during the Halley encounter (Grewing et al., 1987; Reinhardt, 1986; Vega and Giotti, 1986).					
1988					
Phobos 1	Phobos and Mars	orbiter	USSR	7 Jul 1988	Proton-D
Phobos 1 and 2 were Mars orbiters intended for multiple flybys of Phobos with passive remote sensing, active remote sampling, and deployable small Phobos landers. Phobos 1 was lost by a command error on 2 Sep 1988 while enroute to Mars.					

TABLE V

Continued

Phobos 2	Phobos and Mars	orbiter	USSR	12 Jul 1988	Proton-D

Same design as Phobos 1, some differences in science. Entered Mars orbit on 30 Jan 1989. Orbited Phobos at ranges of 200-600 km. Conducted plasma science and studies of Mars and Phobos. Spacecraft lost due to computer electronics failure on March 27, 1989, just days before Phobos lander deployment and the first active surface experiments. Carried international instruments (Phobos, 1989).

1989

Galileo	Asteroid flybys enroute to Jupiter		USA	18 Oct 1989	Shuttle-IUS

Conducted first ever flyby of an asteroid, Gaspra, during spacecraft's initial excursion into the asteroid belt, and flew past Ida on its second and final flythrough of the asteroid belt.

	Gaspra	flyby		29 Oct 1991
	Ida	flyby		28 Aug 1993

Returned imagery, IR spectrophotometry and plasma science at both asteroids. Discovered a small moon of Ida.

1996

NEAR	Eros	orbiter	USA	17 Feb 1996	Delta-2

Near Earth Asteroid Rendezvous mission, first to orbit and land on an asteroid.

	253 Mathilda	flyby		27 Jun 1997
	433 Eros	orbit		14 Feb 2000
	433 Eros	landing		12 Feb 2001

Flew past main belt asteroid Mathilda enroute to Eros rendezvous. Discovered very large craters and a low density C-type composition. NEAR missed its first attempt to rendezvous with Eros in January 1999 when the engine misfired due to a software error. Returned to Eros on 14 February 2000 and successfully inserted into orbit. Obtained imagery, altimetry, infra-red spectrometry, and gamma-ray spectrometry. Found no magnetic field. Mission terminated with a successful landing on the asteroid on 12 February 2001. Conducted gamma-ray spectroscopy on the surface until the mission ended on 28 February 2001 (NEAR, 2000).

1998

Deep Space 1	Spacecraft technology test flight		USA	24 Oct 1998	Delta-2

First flight of a spacecraft powered by an ion engine. More than a dozen new technologies tested.

	Braille	flyby		29 Jul 1999
	Borrelly	flyby		22 Sep 2001

Flew to a successful encounter with near-earth asteroid Braille (1999KD) at 15 km range. The imaging instrument failed to point in the proper direction due to an error in the autonomous operation software. No significant data returned on the asteroid. After a renewed complex set of ion-engine burns, DS-1 flew by Comet Borrelly on 22 September 2001 at a distance of 2200 km and returned high resolution images of the nucleus.

TABLE V
Continued

1999				
Stardust	Wild 2 coma sample return	USA	7 Feb 1999	Delta-2
Scheduled to fly through the coma of Comet Wild 2 on January 2, 2004, take images of the nucleus, make compositional analysis of impacting coma particles, and collect coma particles for return to Earth in January 2006.				

The IACG was continued after the Halley apparition for coordination of other international space science missions. Another organization, the International Halley Watch (IHW), coordinated and collected ground based observations of Halley around the world during the apparition.

Five spacecraft were launched in 1984–1985 and participated in the Halley 'armada': two Soviet (Vega 1 and Vega 2), one European (Giotto) and two Japanese (Suisei and Sakigake). For ESA and Japan's ISAS it was their first experience in exploring another body in the Solar System. The USSR did not originally plan a Halley mission. However, during the planning of a Venera orbiter and balloon mission for 1985, the project scientists and engineers discussed the idea of observing the comet from Venus orbit and then realized that the orbiter spacecraft could be diverted to Halley after flyby of Venus to deploy the entry system. The Vega project was born (Venera + Galley, the latter being the Russian spelling of Halley). This turn of events was engineered by Roald Sagdeev, the Director of IKI at the time (Sagdeev, 1994; Moroz, 2001), and provided an opportunity for the USSR to internationalize its planetary projects. An organization called Intercosmos had existed in the USSR since the 1960s for coordination of international cooperation in space research mainly among Eastern European nations, but this was the first time the activity assumed such a large scale and included Western nations to such a significant extent. The USSR gained enormous influence in the international space community through international cooperation in the Vega missions, setting a precedent for the Phobos and Mars 96 missions to follow.

The Vega missions were the first in the Halley Armada to launch, having their extra duty to perform at Venus. These spacecraft were the first in the venerable Venera/Mars design to take full advantage of the capabilities of this Proton-launched series. NPOL engineers headed by Chief Designer V. M. Kovtunenko were able to add more complexity than had been achieved in previous missions. The Vega spacecraft included a Venus descent probe, a Venus balloon, and a sophisticated cometary payload including an articulated platform for TV cameras and spectrometers. Both spacecraft were successfully launched and carried out their missions at Venus and Halley with near perfection. At Halley the spacecraft flew by at fairly large distance, 8890 km and 8030 km respectively, and conducted imaging, dust and plasma science investigations. Tracking data provided an accurate ephemeris for final targeting of the ESA Giotto spacecraft, which was to follow at much closer flyby distance a few days later.

Japan's Sakigake and Suisei spacecraft were the next to launch. These spacecraft were designed to determine the characteristics of the large extended coma of the comet through remote sensing of the hydrogen atom distribution and *in situ* sensing of the charged particle and magnetic field distribution. These spacecraft were also successful, passing at large distance from the nucleus.

ESA's Giotto spacecraft had the most daring objectives of the Halley Armada, to fly within 600 km of the nucleus and well inside the active coma of the comet. It carried a comprehensive payload for measuring the coma dust impact flux, size and composition of the dust, gas composition, particles and field measurements and a camera. Giotto was the last to launch and the last to arrive, its terminal targeting updated using the data from the two Vega flybys. Giotto obtained a wealth of data on its rocky, impact-riddled ride through the coma including images of coma structure and close-up images of the nucleus (Figure 40) showing the coma jets with tantalizing features on its dark surface. The spacecraft survived its coma passage but the camera was destroyed. Six years later the spacecraft conducted a successful encounter with a second comet, Grigg-Skjellerup, using its remaining suite of operating instruments.

A year after the highly successful series of encounters by the Halley armada, a large international conference summarized the first results obtained from these spacecraft as well as from ground-based observatories (Grewing *et al.*, 1987). The size, shape, albedo and topography of the nucleus were measured and its mass and density estimated. It was shown that the nucleus exhibited characteristics corresponding to the classic Whipple model: a consolidated body composed of ice and rocky material. Physical and chemical properties of coma dust were measured and details of the interaction of the coma with the solar wind were determined. Parent molecules were observed for the first time in the coma gas. Organic matter was found that had not been observed in comets from ground-based observations.

After completion of the highly successful Vega mission, the USSR turned its attention to the Phobos project, leveraging the extensive capabilities of their new spacecraft and the international acclaim won in the Vega missions. Work on this project had begun before the Vega mission, but had proceeded slowly because of the difficulty of developing two complicated projects simultaneously. The goal was to explore in detail the larger of the small Martian moons, and in particular to measure the composition of the surface of Phobos. The possibility of landing the whole spacecraft was rejected in favor of another exotic solution. The plan was to pass above the surface of Phobos at low altitude, use a powerful laser gun to evaporate material from the surface, and then fly through this material analyzing its composition using an on-board mass-spectrometer. In addition, two small stations were to be deployed to the surface of Phobos, one of them stationary and the other mobile ('hopper'). Passive remote sensing experiments were also added for Mars

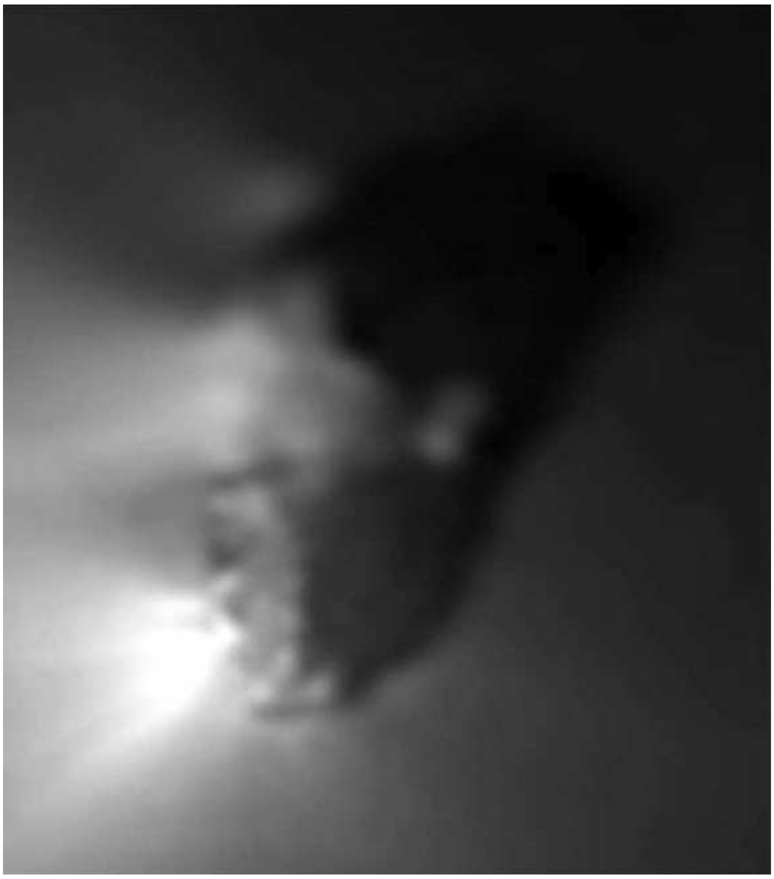

Figure 40. Halley's nucleus from Giotto.

atmospheric science and for Mars and Phobos surface science. These were the only instruments to return science before the Phobos 2 spacecraft was lost.

The Phobos 1 spacecraft was lost en route and the Phobos 2 spacecraft was lost in Mars orbit just prior to its first low altitude pass at Phobos. Phobos 2 did acquire imagery of Phobos to add color to the earlier images from Mariner 9, Viking 1 and Viking 2. Phobos 2 reflectivity spectra show that Phobos' surface material is not similar to carbonaceous chondrites as had been previously supposed. Precise estimates of Phobos' mass and average density were made for the first time after close passes during the last weeks of the mission.

The next major step in small body exploration came from the Galileo spacecraft. Galileo made two passes through the asteroid belt in gathering energy from Earth flybys for its journey outward to Jupiter. On its first pass, Galileo made the first ever close flyby of an asteroid, Gaspra. On its second pass, it flew past the asteroid Ida and discovered its small moon, Dactyl (Figure 41). Both were S-class (stony) asteroids. Galileo took images and conducted IR spectrophotometry and

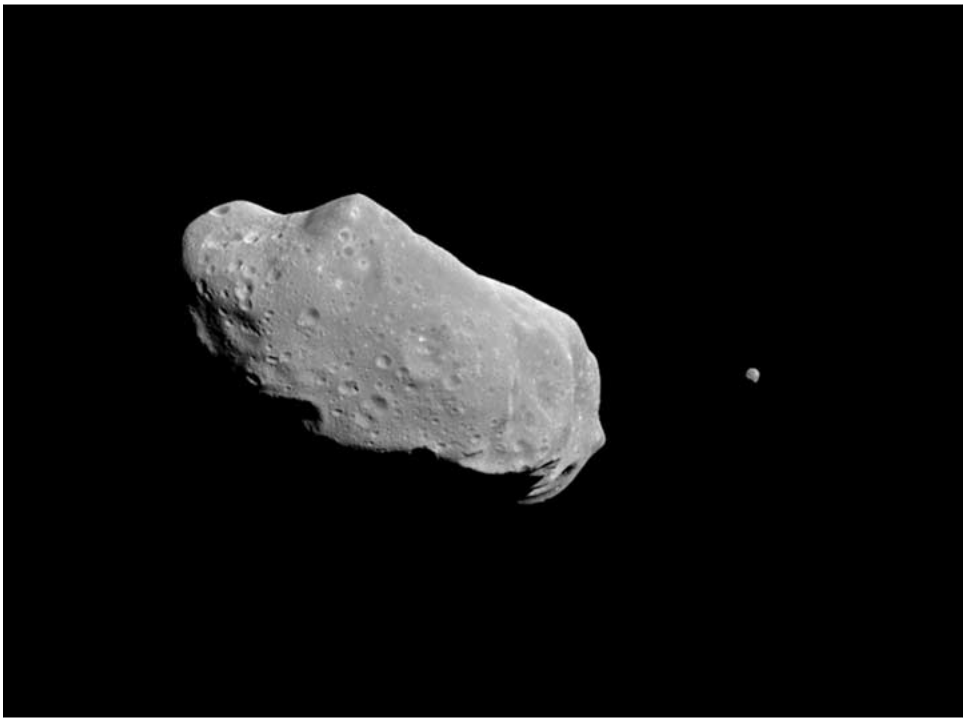

Figure 41. Ida and its moonlet Dactyl from Galileo.

measurements of the plasma environment at each asteroid. The Cassini-Huygens spacecraft, launched in 1997, would later pass through the asteroid belt on its way to Saturn and a far encounter with the small asteroid Masursky.

The Near Earth Asteroid Rendezvous (NEAR) mission launched the first spacecraft dedicated to asteroid exploration in February 1996. The spacecraft flew past the C-class (carbonaceous) main-belt asteroid Mathilda on its way to the near-Earth asteroid Eros. Mathilda was shown to have a very low density and saturated with very large craters, possibly an indication of a rubble-pile structure. NEAR entered orbit about Eros after having missed its first opportunity, and spent one year obtaining imagery, altimetry, IR spectrometry and gamma-ray spectrometry. The mission ended in spectacular fashion with a soft landing on Eros, yielding an extra two weeks of gamma-ray composition measurements on the surface before rotating out of view. The images of both asteroids explored by the NEAR are shown in Figure 42. The last image from NEAR prior to touchdown on Eros is presented in Figure 43.

Exploration of near earth asteroids (NEAs) is of particular importance because many of their orbits come close the Earth, raising the potential for a future collision with Earth. Such a collision could be catastrophic, so the US space program has undertaken careful monitoring of NEAs through ground-based detection and

Figure 42. The two asteroids explored by the NEAR spacecraft, Mathilda (left) and Eros (right).

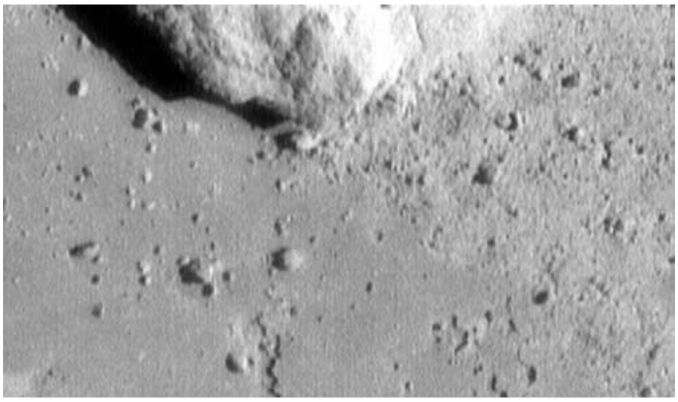

Figure 43. The last image from NEAR prior to touchdown on Eros. The width of the image is 6 meters on the surface.

recovery. Their physical characteristics need to be determined through exploration by spacecraft.

Two other spacecraft were launched late in the 1990s towards small body targets. The Deep Space 1 spacecraft was a test of new spacecraft technologies including a solar electric propulsion stage. It flew by the asteroid Braille in 1999 at only 15 km distance, but its imaging system was not pointed properly. Later it flew past Comet Borrelly at a distance of 2200 km and returned a spectacular series of images of the nucleus of the comet (Figure 44).

The last planetary exploration spacecraft to be launched in the 20th Century was Stardust, a comet coma sample return mission scheduled to fly through the coma of Wild 2 in 2004 and return collected samples to Earth in 2006.

Figure 44. The nucleus of Comet Borrelly from Deep Space 1.

9. Leaving the 20th Century

The history of exploring the Solar System with spacecraft is short, spanning less than 42 years at the end of the 20th Century. Prior to January 1, 2001, there had been 182 launches. Of these, 89 were successful or partly successful, and 3 are currently en route to their ultimate destinations. The exploration of the planets was dominated in the 20th Century by the competition between the USSR and USA. Only 5 of the 182 missions were developed outside the USA and USSR. It was not until 1985 that Europe and Japan launched their own deep space missions.

In the early years of the space race the USSR often got to the Moon, Venus and Mars first, only to be outdone later by the USA. After the race to put humans on the Moon was over in 1969, the USSR accomplished several complex lunar and Venus missions that were conceded by the USA, but the USSR fared poorly at Mars and never attempted to explore the outer solar system. At the end of the 1980s, the Soviet program could be said to have won the space science competition at Venus, but lost it everywhere else. In the 1970s while the USSR focused on Venus landers, lunar rovers and lunar sample return, the USA sent missions to explore almost the entire solar system including the first mission to Mercury, the first planetary orbiter to Mars, the highly complex Viking landers and orbital investigations at Mars, and sent four spacecraft to the outer planets including the monumental Voyager missions. A list of space exploration milestones in the 20th century is given in Table VI.

After a vibrant 1970s, the US program lay fallow in the 1980s and the pendulum swung away from American dominance. The USSR took a leading role by internationalizing its 1984 Vega missions and its 1988 Phobos missions to Mars. This turnabout was not to last. The Soviet bid for leadership of international space science was foiled after the devastating loss of Phobos 1 and 2 in 1988 followed by the failure of the Mars 96 launch in 1996. The loss of Mars 96 demoralized the national program and embarrassed the post-Soviet Russian national government and its new Space Agency. Already beset with financial problems, Russia limited its investment in space science missions. Today the Russian national program of robotic planetary exploration appears to have been postponed indefinitely.

In contrast, the US planetary exploration program recovered in the 1990s. After an 11-year drought between 1978 and 1989, during which the US launched no missions at all, the USSR launched 10 missions, the Japanese 2 and the Europeans one. Between 1989 and 2001 the US has launched 13 missions with only one launched in that time by Russia (Mars 96) and 2 by Japan. Now at the beginning of this new Century there are more nations than ever investing in solar system exploration, and both ESA and Japan are becoming stronger participants. Western space agencies have initiated joint missions such as Cassini/Huygens, and there are scientists involved now from many countries that have no planetary missions of their own. Unlike the Cold War days, there is now free exchange of information and more coordination than in the first 20 years of planetary exploration.

The transition between the two centuries is witness to a robust enterprise of planetary exploration including 2 spacecraft orbiting Mars and another on the way, one orbiting an asteroid, one on the way to sample a comet for return to Earth, one at the Sun-Earth L1 point collecting solar material for return to Earth, one orbiting Jupiter, and another en route to orbit Saturn and drop a probe into the atmosphere of Titan. Many other spacecraft are nearing launch after development begun in the last years of the 20th Century, including a Mercury orbiter, a multiple comet flyby, a comet impactor, a comet rendezvous/lander mission, and an asteroid sample return mission. A list by planet of 20th Century robotic exploration missions that reached their target and returned useful data is given in Table VII.

In addition to these missions scattered around the Solar System, there is an international focus on Mars exploration. There are 2 US rovers and an ESA orbiter/lander under development for launch in 2003, a US orbiter is under development for launch in 2005, and approvals have been given for a French orbiter/netlander mission, an Italian communications satellite and a US rover in 2009. NASA's program for the continuing exploration of Mars began with Mars Pathfinder and Mars Global Surveyor and is working towards a sample return mission. This intensive international campaign at Mars will lead hopefully to the establishment of a permanent robotic outpost on Mars and human missions later in the Century that will reintroduce the Russian experience in planetary exploration.

TABLE VI

Space exploration milestones in the 20th century

Lunar missions		
First lunar mission attempt*	Pioneer 0	1958, August 17
First spacecraft to escape Earth's gravity**	Luna 1	1959, January 2
First spacecraft to fly by the Moon**	Luna 1	1959, January 4
First to impact another celestial body**	Luna 2	1959, September 14
First photographs of the lunar farside**	Luna 3	1959, October 6
First lunar lander**	Luna 9	1966, February 3
First lunar orbiter**	Luna 10	1966, April 3
First image of Earth from the Moon*	Lunar Orbiter 1	1966, August 23
First liftoff from the Moon*	Surveyor 6	1967, November 17
First circumlunar mission with Earth return**	Zond 5	1968, September 20
First piloted circumlunar mission*	Apollo 8	1968, December 24
First piloted landing*	Apollo 11	1969, July 20
First robotic sample return mission**	Luna 16	1970, September 21
First robotic lunar rover (Lunokhod 1)**	Luna 17	1970, November 17
First piloted lunar rover*	Apollo 15	1971, July 30
Mercury missions		
First mission to Mercury (multiple flyby)*	Mariner 10	1974, March 29
Venus missions		
First launch attempt to Venus**	1VA No.1	1961, February 4
First successful mission to Venus (flyby)*	Mariner 2	1962, December 14
First spacecraft to impact another planet**	Venera 3	1966, March 1
First successful planetary entry probe**	Venera 4	1967, October 18
First successful planetary lander**	Venera 7	1970, December 15
First spacecraft to use gravity assist (Venus)*	Mariner 10	1974, February 5
First successful Venus orbiter**	Venera 9	1975, October 22
First photographs from the surface of a planet**	Venera 9	1975, October 22
First radar imagery of Venusian surface**	Venera 15	1983, October 10
First successful planetary balloon**	Vega 1	1985, June 11
Mars missions		
First planetary launch attempt (Mars)**	1M No.1	1960, October 10
First successful mission to Mars (flyby)*	Mariner 4	1965, July 15
First planetary orbiter (Mars)*	Mariner 9	1971, November 14
First spacecraft to impact Mars**	Mars 2	1971, November 27
First landing on Mars**	Mars 3	1971, December 2
First Mars atmospheric probe**	Mars 6	1973, March 12
First successful Mars lander*	Viking 1	1976, July 20
First images from the surface of Mars*	Viking 1	1976, July 20
First planetary rover (Sojourner)*	Mars Pathfinder	1997, July 5
Small bodies missions		
First comet coma distant flyby (G-Z)*	ICE	1985, September 11
First comet nucleus distant flyby (Halley)**	Vega 1	1986, March 6
First comet nucleus close flyby (Halley)***	Giotto	1986, March 14
First asteroid flyby (Gaspra)*	Galileo	1991, October 29
First asteroid orbiter (Eros)*	NEAR	2000, February 14
First asteroid lander (Eros)*	NEAR	2001, February 12
Outer planet missions		
First spacecraft through the asteroid belt*	Pioneer 10	1973
First Jupiter flyby*	Pioneer 10	1973, December 3
First Saturn flyby*	Pioneer 11	1979, September 1
First spacecraft to leave the Solar System*	Pioneer 10	1983, June 13
First Uranus flyby*	Voyager 2	1986, January 24
First Neptune flyby*	Voyager 2	1989, August 25
First Jupiter orbiter*	Galileo	1995, December 7
First Jupiter probe*	Galileo	1995, December 8

*American missions, **Soviet missions, ***European missions.

TABLE VII
Solar system exploration missions in the 20th century

	Mercury USA		Venus USA		Moon USA		Mars USA		Small Bodies USA
1973	Mariner 10 Multiple Flyby	1962	Mariner 2 Flyby	1959	Pioneer 4 Flyby	1964	Mariner 4 Flyby	1978	ICE Comet G-Z Flyby
		1967	Mariner 5 Flyby	1964	Ranger 7 Impactor	1969	Mariner 6 Flyby	1989	Galileo Gaspra/Ida Flybys
		1973	Mariner 10 Flyby	1965	Ranger 8 Impactor	1969	Mariner 7 Flyby	1996	NEAR Matilda Flyby
		1978	Pioneer 12 Orbiter	1965	Ranger 9 Impactor	1971	Mariner 9 Orbiter	1996	NEAR Eros Orbiter
		1978	Pioneer 13 Bus/Probes	1966	Surveyor 1 Lander	1975	Viking 1 Orbiter/Lander	1998	DS-1 Braille/C. Borrelly Flybys
		1989	Magellan Orbiter	1966	Lunar Orbiter 1	1975	Viking 2 Orbiter/Lander	1999	Stardus Wild-2 Coma Return
		1989	Galileo Flyby	1966	Lunar Orbiter 2	1996	Mars Global Surveyor Orbiter		
		1997	Cassini Flyby	1967	Lunar Orbiter 3	1996	Mars Pathfinder Lander		
				1967	Lunar Orbiter 4				
				1967	Lunar Orbiter 5				
				1967	Surveyor 3 Lander				
				1967	Surveyor 5 Lander				
				1967	Surveyor 6 Lander				
				1968	Surveyor 7 Lander				
				1994	Clementine Orbiter				
				1998	Lunar Prospector Orbiter				

All missions which successfully reached their targets and conducted science operations are listed in this table.

TABLE VII
Continued

Mercury		Venus USSR		Moon USSR		Mars USSR		Small Bodies USSR
	1967	Venera 4 Atm Probe	1959	Luna 1 Flyby	1971	Mars 2 Orbiter	1984	Vega 1 Halley Flyby
	1969	Venera 5 Atm Probe	1959	Luna 2 Impactor	1971	Mars 3 Orbiter	1984	Vega 2 Halley Flyby
	1969	Venera 6 Atm Probe	1959	Luna 3 Circumlunar	1973	Mars 4 Flyby	1988	Phobos 2 Orbiter
	1970	Venera 7 Surface Probe	1965	Zond 3 Flyby	1973	Mars 5 Orbiter		
	1972	Venera 8 Surface Probe	1966	Luna 9 Lander	1973	Mars 6 Atm Probe		
	1975	Venera 9 Orbiter/Lander	1966	Luna 10 Orbiter	1988	Phobos 2 Orbiter		
	1975	Venera 10 Orbiter/Lander	1966	Luna 11 Orbiter				
	1978	Venera 11 Flyby/Lander	1966	Luna 12 Orbiter				
	1978	Venera 12 Flyby/Lander	1966	Luna 13 Lander				
	1981	Venera 13 Flyby/Lander	1968	Luna 14 Orbiter				
	1981	Venera 14 Flyby/Lander	1970	Luna 16 Sample Return				
	1983	Venera 15 Orbiter	1970	Luna 17 Lander/Rover				
	1983	Venera 16 Orbiter	1971	Luna 19 Orbiter				
	1984	Vega 1 Flyby/Lander/Balloon	1972	Luna 20 Sample Return				
	1984	Vega 2 Flyby/Lander/Balloon	1973	Luna 21 Lander/Rover				
			1974	Luna 22 Orbiter				
			1976	Luna 24 Sample/Return				

All missions which successfully reached their targets and conducted science operations are listed in this table.

TABLE VII
Continued

	Mercury USA		Venus USA		Moon USA		Mars USA		Small Bodies USA
					ISAS		ISAS		ISAS
				1990	Hiten Flyby	1998	Nozomi Orbiter	1985	Sakigake Halley Flyby
								1985	Suisei Halley Flyby
									ESA
								1985	Giotto Halley/G-K Flybys
	Jupiter USA		**Saturn USA**		**Uranus USA**		**Neptune USA**		
1972	Pioneer 10 Flyby	1973	Pioneer 11 Flyby	1977	Voyager 2	1977	Voyager 2		
1973	Pioneer 11 Flyby	1977	Voyager 1 Flyby						
1977	Voyager 1 Flyby	1977	Voyager 2 Flyby						
1977	Voyager 2 Flyby	1997	Cassini Orbiter						
1989	Galileo Orbiter/Probe		w/ESA Huygens Probe						
			ESA						
		1997	Huygens Titan Probe						

All missions which successfully reached their targets and conducted science operations are listed in this table.

10. A Legacy for the 21st Century

The 42 years of lunar and planetary exploration in the latter half of the 20th Century created an international impetus for solar system exploration and left a robust program of exploration to bridge the two centuries. It also left a legacy of scientific results and new knowledge of our Solar System and its place in the universe. It is hard to remember how little we knew about the Moon and planets at the beginning of the space age in 1957, and how much we have learned since as a result of sending spacecraft throughout the Solar System. We provide a summary of some of the scientific highlights of this enterprise in Table VIII.

TABLE VIII
Highlights of discoveries by 20th century lunar and planetary missions

Moon
Lunar craters are formed by impacts
The far side of the Moon has almost no maria and a huge southern impact basin
The lunar subsurface contains mascons
The lunar crust is enriched in refractory elements
Mercury
Mercury is heavily cratered and shows evidence of tectonics
Mercury has a magnetic field, implying a large iron core
Venus
The Venus surface is hot
The surface pressure on Venus is very high
Some solar visible light reaches the surface of Venus
The Venus surface is essentially volcanic (basaltic)
The Venus surface is globally young
The Venus surface and atmosphere are very dry
The Venus atmosphere consists mainly of CO2.
Relict noble gases have high relative abundance on Venus relative to Earth and Mars
The Venus atmosphere contains active trace species both oxidized and reduced
The Venus global cloud deck lies between 50 and 70 km with hazes above and below
Venus global clouds contain sulfuric acid and other trace acids
The Venus atmosphere super-rotates at the level of the visible cloud layer
The nighttime upper atmosphere is very cold
Venus has a huge hydrogen corona
Unlike the Earth, Venus has no magnetic field
Mars
Mars has a heavily cratered surface over half of its surface
Mars has hemispheric asymmetry:
the north is topographically low and lightly cratered,
the south is topographically high and heavily cratered
Mars has large canyons and giant volcanic structures
Mars has many small and large fluvial-like channels

TABLE VIII

Continued

Mars shows extensive subsurface layering in some locales
Mars shows evidence of massive flooding in the past
Mars shows evidence of flowing water over some periods in the past
Mars shows evidence of large climate changes in the past
Mars shows evidence of recent liquid water extrusion from near surface layers
Martian atmospheric surface pressure is only about 6 mbar and principally CO2
The Martian atmosphere has little water vapor
Mars' southern remnant polar cap is dry ice, the northern remnant cap is water ice
Mars has a huge hydrogen corona
Mars' crust has remnant magnetism
Jupiter
There are giant storms and lightning on Jupiter
The Jovian atmosphere has Solar composition with enhanced light element abundances
The moons of Jupiter, and the other giant planets, are widely varied in nature
Io is a rocky body while Europa, Ganymede and Callisto are rock and ice
Io is a volcanic world with large plumes and a rapidly changing surface
Europa has an exceedingly smooth surface made almost entirely of water ice
Ganymede's surface shows evidence of tectonics
Callisto is heavily cratered with otherwise little evidence of surface change
Ganymede is the only Galilean satellite with a magnetic field
Callisto is undifferentiated. Io, Europa and Ganymede are differentiated
Europa, Ganymede and Callisto show evidence of subsurface oceans
Saturn
Saturn's rings show extensive complex fine structure
Saturn's rings show rapidly changing subtle radial 'spokes'
Some ring structure is caused by 'shepharding' small satellites
The Saturn ring plane is extended with dust beyond the visible rings
Saturn has small satellites sharing the same orbit
Saturn's icy moons show varied surface structure and evidence of change
Titan is completely enveloped in opaque reddish clouds
Titan has an extensive atmosphere with a surface pressure of 1.5 bar
Titan's atmosphere is mainly N_2, with CH_4 as a second (minor) component.
There is the possibility of ethane-methane lakes or oceans on Titan's surface
Titan's atmosphere has traces of complex prebiotic organic compounds
Uranus
Uranus' atmosphere is relatively featureless
Uranus' moon Miranda appears to have been disrupted and reconstructed
Neptune
Neptune has giant atmospheric storms like Jupiter and high, white CH_4 clouds
Triton has a relatively young surface with active dark geysers and a thin N_2 atmosphere

TABLE VIII
Continued

Small bodies
Comet Halley's nucleus is consistent with the icy conglomerate model
Comet Halley's surface is very dark with highly localized jets
Comet Halley's surface was hot (100C) during the spacecraft encounters
Comet Halley's coma contains mainly H_2O and CO with some CO_2 and CH_4
Comet Halley's coma contains some NH_3, but no N_2
Comet Halley's coma contains some organic compounds
Comet Halley's dust contains a fraction rich in refractory C, H, O and N compounds.
Comet Borrelly is also very dark with localized jets
Comet Borrelly's surface has an otherwise asteroidal appearance at high resolution
Asteroid Mathilda, a C-class asteroid, has a very low density and may be a rubble-pile
Asteroid Ida has a small moon
Asteroid Eros has a heavily cratered surface with large rocks
Asteroid Eros shows evidence for segregation of fine dust and formation of plains-like deposits

A whole new Solar System has been defined by space exploration in the 20th Century. Except for Pluto and the Kuiper Belt, the initial reconnaissance of our galactic backyard has been completed by spacecraft. We have surveyed the Moon, Venus, Mars, Jupiter, asteroid Eros, and soon Saturn from orbit, landed on the Moon, Venus, and Mars, and we are now engaged in extensive exploration of Mars. The in-depth exploration that will follow these surveys promises many new and exciting missions. A scientific legacy has been left by the 20th Century that promises many exciting discoveries as we continue into the 21st Century. Table IX provides a brief chronicle of this legacy.

TABLE IX
Timeline of planetary exploration missions in the 20th century

Launch date	L/V	Source	Mission name	Spacecraft	Target	Mission type	Outcome	Description
1958								
17 aug	TA	US (ARPA)	Pioneer 0	Able 1	Moon	Orbiter	fb	Booster exploded.
23 sep	R7E	USSR		Ye-1 No.1	Moon	Impactor	fb	First stage destroyed.
11 oct	TA	US (ARPA)	Pioneer 1	Able 2	Moon	Orbiter	fu	Reached 115 000 km altitude. Returned data on the Van Allen radiation belts.
11 oct	R7E	USSR		Ye-1 No.2	Moon	Impactor	fb	First stage destroyed.
8 nov	TA	US (ARPA)	Pioneer 2	Able 3	Moon	Orbiter	fu	Third stage failure. Reached only 1550 km altitude. Returned no useful data.
4 dec	R7E	USSR		Ye-1 No.3	Moon	Impactor	fb	Second stage premature engine shutdown.
6 dec	J2	US (ABMA)	Pioneer 3	–	Moon	Flyby	fu	Reached 107 500 km altitude. Returned data on the Van Allen radiation belts.
1959								
2 jan	R7E	USSR	Luna 1	Ye-1 No.4	Moon	Impactor	ft	Impact attempt missed moon by 5965 km, but first successful lunar mission and flyby.
3 mar	J2	US (ABMA)	Pioneer 4	–	Moon	Flyby	p	Low injection velocity, flew past Moon at 60 030 km.
18 jun	R7E	USSR		Ye-1A No.5	Moon	Impactor	fb	Second stage guidance failure.
12 sep	R7E	USSR	Luna 2	Ye-1A No.7	Moon	Impactor	s	First successful lunar mission and first successful lunar impact 14 Sep
24 sep	AA	US (NASA)		Atlas-Able 4 (Pioneer)	Moon	Orbiter	fb	Pad explosion during test.
4 oct	R7E	USSR	Luna 3	Ye-2A No.1	Moon	Circumlunar Flyby	s	Circled moon, first far side images.
26 nov	AA	US (NASA)		P-3 (Pioneer)	Moon	Orbiter	fu	Shroud collapsed during launch destroying spacecraft.

TABLE IX
Continued

Launch date	L/V	Source	Mission name	Spacecraft	Target	Mission type	Outcome	Description
1960								
15 apr	R7E	USSR		Ye-3 No.1	Moon	Circumlunar Flyby	fu	Third stage malfunction.
19 apr	R7E	USSR		Ye-3 No.2	Moon	Circumlunar Flyby	fb	First stage distintegrated.
25 sep	AA	US (NASA)		P-30 (Pioneer)	Moon	Orbiter	fu	Launch failed; second stage malfunction.
10 oct	R7M	USSR		1M No.1	Mars	Flyby	fu	Third stage failure. Did not achieve earth orbit.
14 oct	R7M	USSR		1M No.2	Mars	Flyby	fu	Third stage failure. Did not achieve earth orbit.
15 dec	AA	US (NASA)		P-31 (Pioneer)	Moon	Orbiter	fb	Booster exploded.
1961								
4 feb	R7M	USSR	Sputnik 7	1VA No.1	Venus	Probe	fi	Fourth stage failure. Stranded in low Earth orbit.
12 feb	R7M	USSR	Venera 1	1VA No.2	Venus	Probe	fc	Communications failed in transit. Carried pennant in ‘landing apparatus’.
23 aug	AAB	US (NASA)	Ranger 1	P-32	Moon	Deep Space Test	fi	Upper stage failed 2nd burn.
18 nov	AAB	US (NASA)	Ranger 2	P-33	Moon	Deep Space Test	fi	Upper stage failed 2nd burn.
1962								
26 jan	AAB	US (NASA)	Ranger 3	P-34	Moon	Hard Lander	ft	Terminal manuever malfunction. Missed Moon by 37 745 km on 28 Jan.
23 apr	AAB	US (NASA)	Ranger 4	P-35	Moon	Hard Lander	fc	Spacecraft computer failed in Earth orbit. Impacted lunar farside on 26 Apr.

TABLE IX
Continued

Launch date	L/V	Source	Mission name	Spacecraft	Target	Mission type	Outcome	Description
22 jul	AAB	US (NASA)	Mariner 1	P-37	Venus	Flyby	fu	Launch vehicle failed.
25 aug	R7M	USSR	Sputnik 23	2MV-1 No.1	Venus	Atm/Surf Probe	fi	Fourth stage engine failed. Stranded in Earth orbit.
27 aug	AAB	US (NASA)	Mariner 2	P-38	Venus	Flyby	s	First successful planetary mission. Flew by Venus at 34 745 km on 14 Dec.
1 sep	R7M	USSR	Sputnik 24	2MV-1 No.2	Venus	Atm/Surf Probe	fi	Fourth stage failed, stranding vehicle in low Earth orbit.
12 sep	R7M	USSR	Sputnik 25	2MV-2 No.1	Venus	Flyby	fi	Third and fourth stages failed, stranding vehicle in low Earth orbit.
18 oct	AAB	US (NASA)	Ranger 5	P-36	Moon	Hard Lander	fc	Spacecraft power and control system failed in Earth orbit. Passed Moon at 724 km on 21 Oct.
24 oct	R7M	USSR	Sputnik 29	2MV-4 No.1	Mars	Flyby	fi	Fourth stage exploded.
1 nov	R7M	USSR	Mars 1	2MV-4 No.4	Mars	Flyby	fc	Communications failed in transit on 21 Mar 1963.
4 nov	R7M	USSR	Sputnik 31	2MV-3 No.1	Mars	Atm/Surf Probe	fi	Fourth stage failure disintegrated vehicle.
1963								
4 jan	R7M′	USSR	Sputnik 33	Ye-6 No.2	Moon	Lander	fi	Fourth stage failed to ignite, stranding vehicle in Earth orbit.
3 feb	R7M′	USSR		Ye-6 No.3	Moon	Lander	fb	Launch vehicle viered off-course. Did not reach Earth orbit.
2 apr	R7M′	USSR	Luna 4	Ye-6 No.4	Moon	Lander	fc	Spacecraft navigation system failed. Missed Moon by 8451 km on 5 Apr.
11 nov	R7M	USSR	Cosmos 21	3MV-1A No.1	Mars	Test Flight	fi	Test launch. Fourth stage failed, left in Earth orbit.

TABLE IX
Continued

Launch date	L/V	Source	Mission name	Spacecraft	Target	Mission type	Outcome	Description
1964								
30 jan	AAB	US (NASA)	Ranger 6	Ranger A/P-53	Moon	Impactor	ft	Impacted Moon on 2 Feb, but cameras failed to operate.
19 feb	R7M	USSR		3MV-1A No.4A	Venus	Test Flight	fu	Third stage engine failure. Did not reach earth orbit.
21 mar	R7M′	USSR		Ye-6 No.6	Moon	Lander	fu	Third stage engine failure. Did not reach Earth orbit.
27 mar	R7M	USSR	Cosmos 27	3MV-1 No.5	Venus	Atm/Surf Probe	fi	Fourth stage engine did not ignite. Did not leave Earth orbit.
2 apr	R7M	USSR	Zond 1	3MV-1 No.4	Venus	Atm/Surf Probe	fc	Communications failed in transit.
20 apr	R7M′	USSR		Ye-6 No.5	Moon	Lander	fu	Upper stage failures. Did not reach earth orbit.
28 jul	AAB	US (NASA)	Ranger 7	Ranger B/P-54	Moon	Impactor	s	First completely successful US lunar mission. Returned 4316 photos on 31 Jul.
5 nov	AAD	US (NASA)	Mariner 3	Mariner-64C	Mars	Flyby	fu	Shroud failed to jettison properly, damaging spacecraft. Transmission ceased after 9 hrs.
28 nov	AAD	US (NASA)	Mariner 4	Mariner-64D	Mars	Flyby	s	First successful Mars mission. Returned 22 photos on 14 Jul 1965.
30 nov	R7M	USSR	Zond 2	3MV-4 No.2	Mars	Flyby	fc	Communications failed in transit after one month.
1965								
17 feb	AAB	US (NASA)	Ranger 8	Ranger C	Moon	Impactor	s	Returned 7137 photos of Sea of Tranquility on 20 Feb.
12 mar	R7M′	USSR	Cosmos 60	Ye-6 No.9	Moon	Lander	fi	Fourth stage failed to ignite, left in Earth orbit.
21 mar	AAB	US (NASA)	Ranger 9	Ranger D	Moon	Impactor	s	Returned 5814 photos. Impact into Crater Alphonsus on 24 Mar.
10 apr	R7M	USSR		Ye-6 No.8	Moon	Lander	fu	Third stage engine failure. Did not reach earth orbit.

TABLE IX
Continued

Launch date	L/V	Source	Mission name	Spacecraft	Target	Mission type	Outcome	Description
9 may	R7M	USSR	Luna 5	Ye-6 No.10	Moon	Lander	ft	Guidance and retro-rockets malfunctioned. Crashed into Sea of Clouds on 12 May.
8 jun	R7M	USSR	Luna 6	Ye-6 No.7	Moon	Lander	fc	Mid-course maneuver failed. Missed the Moon by 160 935 km on 11 Jun.
18 jul	R7M	USSR	Zond 3	3MV-4 No.3	Moon	Flyby	s	Photographed the lunar farside on 20 Jul. Test of Mars spacecraft and launcher.
					Mars	Test Flight	fc	Communications lost before reaching Mars distance.
4 oct	R7M	USSR	Luna 7	Ye-6 No.11	Moon	Lander	ft	Crashed into the Ocean of Storms near Kepler on 7 Oct.
12 nov	R7M	USSR	Venera 2	3MV-4 No.4	Venus	Flyby	ft	Communications failed during Venus flyby on 27 Feb 1966.
16 nov	R7M	USSR	Venera 3	3MV-3 No.1	Venus	Atm/Surf Probe	fc	Communications failed 17 days before arrival. Silent probe entered on 1 Mar 1966.
23 nov	R7M	USSR	Cosmos 96	3MV-4 No.6	Venus	Flyby	fi	Upper stage failures, did not leave Earth orbit.
3 dec	R7M	USSR	Luna 8	Ye-6 No.12	Moon	Lander	ft	Crashed into the Ocean of Storms near Galilaei on 6 Dec.
1966								
31 jan	R7M	USSR	Luna 9	Ye-6M No.202/13	Moon	Lander	s	First successful lunar lander on 3 Feb. Returned pictures of the surface.
1 mar	R7M	USSR	Cosmos 111	Ye-6S No.204	Moon	Orbiter	fi	Trans-lunar injection failed. Not listed by Chertok.
31 mar	R7M	USSR	Luna 10	Ye-6S No.206	Moon	Orbiter	s	First successful lunar orbiter on 3 Apr.
30 may	AC	US (NASA)	Surveyor 1	Surveyor-A	Moon	Lander	s	First US lunar lander successful 2 Jun. Returned 11,237 images.
10 aug	AAD	US (NASA)	Lunar Orbiter 1	LO-A	Moon	Orbiter	s	First US lunar orbiter successful on 14 Aug. Photographic mapper for Apollo.

TABLE IX
Continued

Launch date	L/V	Source	Mission name	Spacecraft	Target	Mission type	Outcome	Description
24 aug	R7M	USSR	Luna 11	Ye-6LF No.101	Moon	Orbiter	p	Lunar orbit photo and science mission. No images returned.
20 sep	AC	US (NASA)	Surveyor 2	Surveyor-B	Moon	Lander	ft	Crashed southeast of Copernicus on 22 Sep.
22 oct	R7M	USSR	Luna 12	Ye-6LF No.102	Moon	Orbiter	s	Lunar orbit photo and science mission.
6 nov	AAD	US (NASA)	Lunar Orbiter 2	LO-B	Moon	Orbiter	s	Lunar orbital photographic mapper for Apollo orbited on 9 Nov.
21 dec	R7M	USSR	Luna 13	Ye-6M No.205/14	Moon	Lander	s	Lunar surface science and images. Landed 24 Dec.
1967								
5 feb	AAD	US (NASA)	Lunar Orbiter 3	LO-C	Moon	Orbiter	s	Lunar photographic mapper for Apollo orbited 8 Feb. Imaged Surveyor 1 on the surface.
17 apr	AC	US (NASA)	Surveyor 3	Surveyor-C	Moon	Lander	s	Lunar surface science and images. Landed 20 Apr. Scooped soil.
4 may	AAD	US (NASA)	Lunar Orbiter 4	LO-D	Moon	Orbiter	s	Lunar photographic mapper for Apollo orbited 8 May.
16 may	R7M	USSR	Cosmos 159	Ye-6LS No.111	Moon	Orbiter Test Flight	fu	Fourth stage burn insufficient for very high Earth orbit.
12 jun	R7M	USSR	Venera 4	1V No.310	Venus	Atm/Surf Probe	s	First successful planetary atmospheric probe Oct 18.
14 jun	AAD	US (NASA)	Mariner 5	Mariner-67E	Venus	Flyby	s	Flew by Venus at 3990 km on 19 Oct.
17 jun	R7M	USSR	Cosmos 167	1V No.311	Venus	Atm/Surf Probe	fi	Failed to depart low Earth orbit.
14 jul	AC	US (NASA)	Surveyor 4	Surveyor-D	Moon	Lander	ft	Lost contact minutes before landing on 17 Jul.
1 aug	AAD	US (NASA)	Lunar Orbiter 5	LO-E	Moon	Orbiter	s	Entered lunar polar orbit on 5 Aug for scientific photographic mapping.
8 sep	AC	US (NASA)	Surveyor 5	Surveyor-E	Moon	Lander	s	Lunar surface science and images. Landed in Sea of Tranquility on 11 Sep

TABLE IX
Continued

Launch date	L/V	Source	Mission name	Spacecraft	Target	Mission type	Outcome	Description
27 sep	PrD	USSR		7K-L1 No.4L	Moon	Circumlunar/Return	fb	Circumlunar test of unpiloted Soyuz lunar craft in Earth orbit. Booster failed.
7 nov	AC	US (NASA)	Surveyor 6	Surveyor-F	Moon	Lander	s	Lunar surface science and images. Conducted short hop for stereo imaging.
22 nov	PrD	USSR		7K-L1 No.5L	Moon	Circumlunar/Return	fu	Circumlunar test of unpiloted Soyuz lunar craft in Earth orbit. Second stage failure.
1968								
7 jan	AC	US (NASA)	Surveyor 7	Surveyor-G	Moon	Lander	s	Landed 10 Jan and conducted lunar surface science and imagery. Dug trench in soil.
7 feb	R7M	USSR		Ye-6LS No.112	Moon	Orbiter	fu	Third stage terminated early at 524 s, ran out of propellant.
2 mar	PrD	USSR	Zond 4	7K-L1 No.6L	Moon	Lunar Distance Test Flight	ft	Test of unpiloted Soyuz lunar craft to lunar distance. Self-destructed before touchdown.
7 apr	R7M	USSR	Luna 14	Ye-6LS No.113	Moon	Orbiter	s	Orbited 10 Apr and mapped lunar gravity field.
22 apr	PrD	USSR		7K-L1 No.7L	Moon	Circumlunar/Return	fu	Circumlunar test of unpiloted Soyuz lunar craft. Second stage shutdown.
14 sep	PrD	USSR	Zond 5	7K-L1 No.9L	Moon	Circumlunar/Return	s	First circumlunar flight and return to earth on 21 Sep.
10 nov	PrD	USSR	Zond 6	7K-L1 No.12L	Moon	Circumlunar/Return	ft	Circumlunar flight and return to earth on 17 Nov. Crash on landing.
21 dec	S5	US (NASA)	Apollo 8	CSM103	Moon	Piloted Orbiter	s	First human piloted mission to the Moon. Entered orbit on 24 Dec. 10 orbits.

TABLE IX
Continued

Launch date	L/V	Source	Mission name	Spacecraft	Target	Mission type	Outcome	Description
1969								
5 jan	R7M	USSR	Venera 5	2V No.330	Venus	Atm/Surf Probe	s	Returned atmospheric science on 16 may. Crushed at 18 km altitude.
10 jan	R7M	USSR	Venera 6	2V No.331	Venus	Atm/Surf Probe	s	Returned atmospheric science on 17 May. Crushed at 18 km altitude.
20 jan	PrD	USSR		7K-L1 No.13L	Moon	Circumlunar/Return	fu	Circumlunar test of unpiloted Soyuz lunar craft in Earth orbit. Second stage failure.
19 feb	PrD	USSR		Ye-8 No.201	Moon	Lander/Rover	fu	Shroud failure, vehicle distintegrated.
21 feb	N1	USSR		7K-L1S No.3S	Moon	Orbiter/Return	fb	First N1 launch. First stage failed in flight.
25 feb	AC	US (NASA)	Mariner 6	Mariner-69F	Mars	Flyby	s	Successful. Returned 75 images during flyby on 31 Jul.
27 mar	AC	US (NASA)	Mariner 7	Mariner-69G	Mars	Flyby	s	Successful. Returned 126 images during flyby on 4 Aug.
27 mar	PrD	USSR		M-69 No.521	Mars	Orbiter	fu	Planned atm probe deleted. Third stage exploded.
2 apr	PrD	USSR		M-69 No.522	Mars	Orbiter	fb	Planned atm probe deleted. Booster exploded.
18 may	S5	US (NASA)	Apollo 10	CSM106/LM4	Moon	Piloted Orbiter	s	Orbited 22 May and tested lunar lander in lunar orbit.
14 jun	PrD	USSR		Ye-8-5 No.402	Moon	Sample Return	fu	Fourth stage failed to ignite.
3 jul	N1	USSR		7K-L1S No.5L	Moon	Orbiter/Return	fb	Second N1 launch. First stage exploded at liftoff.
13 jul	PrD	USSR	Luna 15	Ye-8-5 No.401	Moon	Sample Return	ft	Crashed in the Sea of Crises during landing attempt on 21 July after 52 orbits.
16 jul	S5	US (NASA)	Apollo 11	CSM107/LM5	Moon	Piloted Orbiter/Lander	s	First human landing on the Moon, 20 July, 1969. Returned lunar rocks and soil on 24 Jul.

TABLE IX
Continued

Launch date	L/V	Source	Mission name	Spacecraft	Target	Mission type	Outcome	Description
7 aug	PrD	USSR	Zond 7	7K-L1 No.11	Moon	Circumlunar/Return	s	Successful. Returned to Earth on 14 Aug.
23 sep	PrD	USSR	Cosmos 300	Ye-8-5 No.403	Moon	Sample Return	fi	Fourth stage failed to ignite for translunar injection. Re-entered 27 Sep.
22 oct	PrD	USSR	Cosmos 305	Ye-8-5 No.404	Moon	Sample Return	fi	Fourth stage misfire. Re-entered 24 Oct.
14 nov	S5	US (NASA)	Apollo 12	CSM108/LM6	Moon	Piloted Orbiter/Lander	s	Successful precision landing 156 meters from Surveyor 3. Returned parts of Surveyor 3.
1970								
6 feb	PrD	USSR		Ye-8-5 No.405	Moon	Sample Return	fu	Second stage premature shutdown at 127 s mark.
11 apr	S5	US (NASA)	Apollo 13	CSM109/LM7	Moon	Piloted Orbiter Lander	fc	Support module explosion en route. Astronauts returned safely on 17 Apr.
17 aug	R7M	USSR	Venera 7	3V No.630	Venus	Atm/Surf Probe	s	First successful planetary lander on Dec 15, 1970. Transmitted for 23 min on the surface.
22 aug	R7M	USSR	Cosmos 359	3V No.631	Venus	Atm/Surf Probe	fi	Failed to depart low Earth orbit.
12 sep	PrD	USSR	Luna 16	Ye-8-5 No.406	Moon	Sample Return	s	First robotic lunar sample return. Landed 20 Sep, returned 24 Sep.
20 oct	PrD	USSR	Zond 8	7K-L1 No.14	Moon	Circumlunar/Return	s	Successful. Returned to Earth on 27 Oct.
10 nov	PrD	USSR	Luna 17	Ye-8 No.203	Moon	Lander/Rover	s	First lunar rover, Lunokhod 1, traveled surface for 11 lunar days.
1971								
31 jan	S5	US (NASA)	Apollo 14	CSM110/LM8	Moon	Piloted Orbiter/Lander	s	Successful follow up to Apollo 13. Landed in Fra Mauro on 5 Feb.
9 may	AC	US (NASA)	Mariner 8	Mariner-71H	Mars	Orbiter	fu	Centaur stage failure.
10 may	PrD	USSR	Cosmos 419	M-71 No.170	Mars	Orbiter	fi	Fourth stage failed to re-ignite, left in low earth orbit.

TABLE IX
Continued

Launch date	L/V	Source	Mission name	Spacecraft	Target	Mission type	Outcome	Description
19 may	PrD	USSR	Mars 2	M-71 No.171	Mars	Orbiter/Lander	p	Orbiter successful on 27 Nov, completed 362 orbits. Lander crashed, first artifact on Mars.
28 may	PrD	USSR	Mars 3	M-71 No.172	Mars	Orbiter/Lander	p	First lander on Mars, but failed after 20 sec on 2 Dec. Orbiter completed 20 orbits.
30 may	AC	US (NASA)	Mariner 9	Mariner-71I	Mars	Orbiter	s	First successful Mars and planetary orbiter on 13 Nov.
26 jul	S5	US (NASA)	Apollo 15	CSM112/LM10	Moon	Piloted Orbiter/Lander/Rover	s	First human-carrying lunar rover. Deployed lunar subsatellite on 4 Aug.
2 sep	PrD	USSR	Luna 18	Ye-8-5 No.407	Moon	Sample Return	ft	Lost communications during landing attempt on 11 Sep.
28 sep	PrD	USSR	Luna 19	Ye-8LS No.202	Moon	Orbiter	s	Lunar orbital photographic and gravity field mapping.
1972								
14 feb	PrD	USSR	Luna 20	Ye-8-5 No.408	Moon	Sample Return	s	Returned samples on 25 Feb.
2 mar	AC	US (NASA)	Pioneer 10	Pioneer-F	Jupiter	Flyby	s	First Jupiter flyby on 3 Dec, 1973. First to leave Solar System in 1983.
27 mar	R7M	USSR	Venera 8	3V No.670	Venus	Atm/Surf Probe	s	Successful atm. probe and survived landing on 22 July.
31 mar	R7M	USSR	Cosmos 482	3V No.671	Venus	Atm/Surf Probe	fi	Fourth stage misfired, failed to depart low Earth orbit.
16 apr	S5	US (NASA)	Apollo 16	CSM113/LM11	Moon	Piloted Orbiter/Lander/Rover	s	Deployed lunar subsatellite on 24 Apr. Landed in DesCarte 20 Apr. Carried rover.
23 nov	N1	USSR		7K-LOK No.6A	Moon	Orbiter/Return	fb	Fourth N1 launch. Booster exploded in flight.

TABLE IX
Continued

Launch date	L/V	Source	Mission name	Spacecraft	Target	Mission type	Outcome	Description
7 dec	S5	US (NASA)	Apollo 17	CSM114/LM12	Moon	Piloted Orbiter/ Lander/Rover	s	Final Apollo mission, first and last to carry a scientist. Landed 11 Dec, returned 19 Dec.
1973								
8 jan	PrD	USSR	Luna 21	Ye-8 No.204	Moon	Lander/Rover	s	Deployed Lunokhod 2 rover on 15 Jan. Ceased operations on 5th lunar day.
5 apr	AC	US (NASA)	Pioneer 11	Pioneer-G	Jupiter	Flyby	s	Flew past Jupiter on 4 Dec 1974.
					Saturn	Flyby	s	Flew past Saturn on 1 Sep 1979.
21 jul	PrD	USSR	Mars 4	M-73 No.52S	Mars	Orbiter	ft	Failed to achieve Mars orbit on 10 Feb 1974.
25 jul	PrD	USSR	Mars 5	M-73 No.53S	Mars	Orbiter	s	Entered orbit 12 Feb 1974, completed 22 orbits, failed in early March.
5 aug	PrD	USSR	Mars 6	M-73 No.50P	Mars	Flyby/Lander	ft	Lander returned descent data on 12 Mar 1974, but no communication from surface.
9 aug	PrD	USSR	Mars 7	M-73 No.51P	Mars	Flyby/Lander	ft	Failed to deliver lander to proper trajectory, missed the planet by 1300 km on 9 Mar 1974.
3 nov	AC	US (NASA)	Mariner 10	Mariner-73J	Venus	Flyby	s	Flew by Venus on 5 Feb 1974.
					Mercury	Flyby	s	Three flybys: 29 Mar 1974, 21 Sep 1974 and 16 Mar 1975.
1974								
29 may	PrD	USSR	Luna 22	Ye-8LS No.206	Moon	Orbiter	s	Lunar orbital photographic mapping and remote surface elemental composition measurements.
28 oct	PrD	USSR	Luna 23	Ye-8-5M No.410	Moon	Sample Return	ft	Landed 6 Nov in Sea of Crises. Sampler damaged in landing. Lasted 3 days, no return.

TABLE IX
Continued

Launch date	L/V	Source	Mission name	Spacecraft	Target	Mission type	Outcome	Description
1975								
8 jun	PrD	USSR	Venera 9	4V-1 No.660	Venus	Orbiter Lander	s	Landed 22 Oct. First BW images of Venus at the surface.
14 jun	PrD	USSR	Venera 10	4V-1 No.661	Venus	Orbiter Lander	s	Landed 25 Oct. Same science as Venera 9
20 aug	T3EC	US (NASA)	Viking 1	Viking-B	Mars	Orbiter/Lander	s	Orbited Mars 19 June 1976. Deployed first successful Mars lander on 20 Jul.
9 sep	T3EC	US (NASA)	Viking 2	Viking-A	Mars	Orbiter/Lander	s	Orbited Mars 7 Aug 1976. Deployed successful lander on 3 Sep.
16 oct	PrD	USSR		Ye-8-5M No.412	Moon	Sample Return	fu	Fourth stage failed.
1976								
9 aug	PrD	USSR	Luna 24	Ye-8-5M No.413	Moon	Sample Return	s	Landed 18 Aug and returned core samples on 23 Aug.
1977								
20 aug	T3EC	US (NASA)	Voyager 2	Voyager-2	Jupiter	Flyby	s	Explored Jupiter system on 9 Jul 1979.
					Saturn	Flyby	s	Explored Saturn system on 25 Aug 1981.
					Uranus	Flyby	s	Explored Uranus system on 24 Jan 1986.
					Neptune	Flyby	s	Explored Neptune system on 25 Aug 1989.
5 sep	T3EC	US (NASA)	Voyager 1	Voyager-1	Jupiter	Flyby	s	Explored Jupiter system on 5 Mar 1979.
					Saturn	Flyby	s	Explored Saturn system on 12 Nov 1980.

TABLE IX
Continued

Launch date	L/V	Source	Mission name	Spacecraft	Target	Mission type	Outcome	Description
1978								
20 may	AC	US (NASA)	Pioneer 12 (Pioneer Venus 1)	PV Orbiter	Venus	Orbiter	s	Orbited 4 Dec. Conducted atm science and first planetary radar mapping.
8 aug	AC	US (NASA)	Pioneer 13 (Pioneer Venus 2)	PV Multiprobe	Venus	Entry Bus/Atm Probes	s	Entered 9 Dec. Kamikaze bus plus one large and three small atm probes all successful.
12 aug	D	US (NASA)	Int'l Comet Explorer	Int'l Comet Explorer	Comet G-Z	Flyby	s	ISEE-3 diverted to Giaccobini-Zinner in 1983. First comet flyby 11 Sep 1985.
9 sep	PrD	USSR	Venera 11	4V-1 No.360	Venus	Flyby/Lander	s	Landed 25 Dec. Atmospheric science. Imaging failed.
14 sep	PrD	USSR	Venera 12	4V-1 No.361	Venus	Flyby/Lander	s	Landed 21 Dec. Same science as Venera 11, imaging also failed.
1979								
			(No Missions)	(No Missions)		(No Missions)		
1980								
			(No Missions)	(No Missions)		(No Missions)		
1981								
30 oct	PrD	USSR	Venera 13	4V-1M No.760	Venus	Flyby/Lander	s	Landed 1 Mar 1982. First color imagery from Venus surface.
4 nov	PrD	USSR	Venera 14	4V-1M No.761	Venus	Flyby/Lander	s	Landed 5 Mar 1982. Same science as Venera 13.
1982								
			(No Missions)	(No Missions)		(No Missions)		
1983								
2 jun	PrD	USSR	Venera 15	4V-2 No.860	Venus	Orbiter	s	Orbited Oct 10. Radar mapper.

TABLE IX
Continued

Launch date	L/V	Source	Mission name	Spacecraft	Target	Mission type	Outcome	Description
7 jun	PrD	USSR	Venera 16	4V-2 No.861	Venus	Orbiter	s	Orbited Oct 14. Radar mapper. Same coverage as Venera 16.
1984								
15 dec	PrD	USSR	Vega 1	5VK No.901	Venus	Flyby/Lander/Balloon	s	Deployed Lander and Balloon at Venus on 11 Jun 1985.
					Halley	Flyby	s	Flew by Halley at 8890 km 6 Mar 1986.
21 dec	PrD	USSR	Vega 2	5VK No.902	Venus	Flyby/Lander/Balloon	s	Deployed Lander and Balloon at Venus on 15 Jun 1985.
					Halley	Flyby	s	Flew by Halley at 8030 km 9 Mar 1986.
1985								
7 jan	M3S2	Japan (ISAS)	Sakigake	MS-T5	Halley	Flyby	s	Very distant Halley flyby on 8 Mar 1986.
2 jul	A1	ESA	Giotto	Giotto	Halley	Flyby	s	Close Halley flyby at 596 km on 14 Mar 1986. Nucleus imaging.
					Comet G-S	Flyby	s	Flew by Grigg-Skjellerup on 10 Jul 1992.
18 aug	M3S2	Japan (ISAS)	Suisei	Planet-A	Halley	Flyby	s	Distant Halley flyby at 151 000 km on 14 Mar 1986.
1986								
			(No Missions)	(No Missions)		(No Missions)		
1987								
			(No Missions)	(No Missions)		(No Missions)		
1988								
7 jul	PrD	USSR	Phobos 1	1F No.101	Mars	Orbiter/Phobos Lander	fc	Lost en route due to a command error on 1 Sep.

TABLE IX
Continued

Launch date	L/V	Source	Mission name	Spacecraft	Target	Mission type	Outcome	Description
12 jul	PrD	USSR	Phobos 2	1F No.102	Mars	Orbiter/Phobos Lander	ft	Entered Mars orbit on 30 Jan 1989. Failed on 27 Mar just prior to first Phobos encounter.
1989								
4 may	STS	US (NASA)	Magellan	Magellan	Venus	Orbiter	s	Radar mapper orbited on 10 Aug 1990. Completed high resolution coverage of entire planet.
18 oct	STS	US (NASA)	Galileo	Galileo	Venus	Flyby	s	10 feb 90
					Earth	Flyby	s	8 dec 90
					Gaspra	Flyby	s	29 okt 91
					Earth	Flyby	s	8 dec 92
					Ida	Flyby	s	28 aug 93
					Jupiter	Atm Probe	s	Successful entry on 7 Dec 1996. Relayed data through main s/c prior to JOI.
					Jupiter	Orbiter	s	Entered Jupiter orbit on 7 Dec 1996. Missed data on first Io flyby prior to JOI.
1990								
24 jan	M3S2	Japan (ISAS)	Hiten-	MUSES-A	Moon	Flyby	s	Flew by Moon and deployed Hagoromo.
			Hagoromo		Moon	Orbiter	ft	Deployed from Hiten. No communications received post-deployment.
1991								
			(No Missions)	(No Missions)		(No Missions)		

TABLE IX
Continued

Launch date	L/V	Source	Mission name	Spacecraft	Target	Mission type	Outcome	Description
1992								
25 sep	T3C	US (NASA)	Mars Observer	Mars Observer	Mars	Orbiter	ft	Lost. Propulsion system failed 3 days prior to Mars orbit insertion.
1993			(No Missions)	(No Missions)		(No Missions)		
1994								
25 jan	T2G	US (DoD/NASA)	Clementine	Clementine	Moon	Orbiter	s	Entered lunar orbit 19 Feb and conducted global photographic and spectral mapping.
					Geographos	Flyby	fc	Departed lunar orbit on 3 May and failed enroute to asteroid Geographos on 7 May.
1995			(No Missions)	(No Missions)		(No Missions)		
1996								
17 feb	D2	US (NASA)	Near Earth Asteroid Rendezvous	NEAR	Asteroid	Orbiter	s	NEAR flew by asteroid Mathilda en route to orbiting Eros. First to orbit an asteroid.
7 nov	D2	US (NASA)	Mars Global Surveyor	MGS	Mars	Orbiter	s	Entered orbit 11 Sep 1997. First aerobraking to achieve close mapping orbit.
16 nov	PrD	USSR	Mars 96	M1 No.520	Mars	Orbiter/Landers	fu	Fourth stage failure, re-entered atmosphere.

TABLE IX

Continued

Launch date	L/V	Source	Mission name	Spacecraft	Target	Mission type	Outcome	Description
4 dec	D2	US (NASA)	Mars Pathfinder	Mars Pathfinder	Mars	Lander	s	Landed on 4 Jul 1997 using air bags.
						Rover	s	First Mars rover ‘Sojourner’ deployed from lander on 6 Jul.
1997								
15 oct	T4BC	US (NASA) and	Cassini-Huygens	Cassini-Huygens	Saturn	Orbiter	e	Orbiter with Titan probe attached en route to Saturn.
		Europe (ESA)			Titan	Atm/Surf Probe	e	Attached to Cassini Saturn Orbiter. Will be dispatched on third orbit.
					Venus	Flyby	s	26 apr 98
					Venus	Flyby	s	24 jun 99
					Earth	Flyby	s	17 aug 99
					Jupiter	Flyby	e	dec 00
1998								
7 jan	A2	US (NASA)	Lunar Prospector	Lunar Prospector	Moon	Orbiter	s	UV/Vis and IR mapper entered orbit on 11 Jan. Found evidence for water at the poles.
3 jul	M5	Japan (ISAS)	Nozomi	Planet-B	Mars	Orbiter	e	En route to Mars.
24 oct	D2	US (NASA)	Deep Space 1	DS-1	Asteroid	Test Flight	p	Technology test flew by asteroid 1992KD and Comet Borrelly. Science success only at Borrelly.
11 dec	D2	US (NASA)	Mars Climate Orbiter	MCO	Mars	Orbiter	ft	Failed to achieve Mars orbit due to navigation error on 23 Sep 1999. Impacted atmosphere.

TABLE IX
Continued

Launch date	L/V	Source	Mission name	Spacecraft	Target	Mission type	Outcome	Description
1999								
3 jan	D2	US (NASA)	Mars Polar Lander	MPL	Mars	Lander	ft	Failed during entry on 3 Dec. Also carried two separate small 'DS-2' penetrators.
		US (NASA)	Deep Space 2	DS-2	Mars	Penetrators (2)	ft	Carried to Mars by the Mars Polar Lander carrier vehicle.
7 feb	D2	US (NASA)	Stardust	Stardust	Comet	Sample Return	e	En route to Comet Wild-2.
2000								
			(No Missions)	(No Missions)		(No Missions)		

Launch Vehicle Codes: R7E: Luna; R7M: Molniya; R7M′: Molniya modified for spacecraft control of upper stages; PrD: Proton with Block D restartable upper stage; N1: N1-L3 Soviet Moon launcher similar to the US Saturn 5; TA: Thor-Able; J2: Juno 2 (modified Jupiter-C); AA: Atlas-Agena; AAB: Atlas-Agena B; AAD: Atlas-Agena D; AC: Atlas-Centaur; T2G: Titan 2G; T3EC: Titan 3E Centaur; T3C: Titan 3C; T4BC: Titan 4B Centaur; D: Delta; D2: Delta 2; A2: Athena 2; S5: Saturn 5; STS: Space Transporation System (Space Shuttle) with Interim Upper Stage (IUS); A1: ESA Ariane 1; M3S2: ISAS M3S2; M5: ISAS M5.
Outcome Codes: fb: booster failure; fu: upper stage failure; fi: interplanetary trajectory injection failure; fc: failure in transit during cruise; ft: failure at the target; p: partial success; s: success; e: enroute.

References

In addition to the references cited in the text, we have added some references in the Tables for sources containing more information about particular missions or programs. There are also two additional sources containing reference information about many planetary missions (Glushko, 1985; Siddiqi, 2002). The Russian reader would recognize the Encyclopedia 'Cosmonautics' (Glushko, 1985) as a very useful and reliable source. However, it was published a long time ago and contains almost nothing about failed Soviet missions, omitting an important part of the history. Siddiqi (2002) has recently published a chronicle listing all planetary missions, both successful and unsuccessful.

Anon.: 1959, *Pervye photografii obratnoi storony Luny*, Moskva, Izdatelstvo AN SSSR.

Anon.: 1960, *Atlas obratnoi storony Luny*, Moskva, Izdatelstvo AN SSSR.

Anon.: 1966, *Pervye panoramy lunnoi poverhnosti*, Moskva, Nauka.

Barsukov, V. I., Basilevsky, A. T., Volkov, V. P., and Zharkov, V. N. eds.: 1992, *Venus Geology, Geochemistry, and Geophysics, Research results from the USSR* The University of Arizona Press, Tucson, London.

Bergstrahl J. T., Miner E. D., and Mattheus M. S. eds.: 1991, *Uranus*, The University of Arizona Press, Tucson.

Burns J. A. and Matthews M. S., eds.: 1986, *Satellites*, The University of Arizona Press, Tucson.

Bougher, S. W., Hunten, D. M., and Phillips, R. J., eds.: 1997, *Venus II*, The University of Arizona Press, Tucson, Arizona.

Chertok B. E.: 1999a, *Rakety i liudi. Lunnaya gonka*, Moskva, Mashinostroenie (in Russian).

Chertok B. E.: 1999b, *Rakety i liudi (2 ed.)*, Moskva, Mashinostroenie (in Russian).

Chertok B. E.: 1999c, *Rakety i liudi. Fili, Podlipki, Tyuratam*, Moskva, Mashinostroenie (in Russian).

Chertok B. E.: 1999d, *Rakety i liudi. Gorjachie dni holodnoi voiny*, Moskva, Mashinostroenie (in Russian).

(Clementine*) 1994, *Science* **266**, 1835–1862.

Cruikshank D. P., ed.: 1995, *Neptune and Triton*, The University of Arizona Press, Tucson.

Dunne J.A., and Burgess E.: 1978, *The Voyage of Mariner 10: Mission to Venus and Mercury*, NASA **SP-424**.

Fimmel R. O., *et al.*: 1977, *Pioneer Odyssey*, NASA **SP-396**.

(Galileo*) 1996, *Science* **274**, 377–401.

(Galileo Probes Jupiter's Atmosphere*) 1996, *Science* **272**, 837–860.

Gehrels T., ed.: 1974, *Jupiter*, The University of Arizona Press, Tucson.

Gehrels T. and Matthews M. S. eds.: 1982, *Saturn*, The University of Arizona Press, Tucson.

Glushko, V. P. ed.: 1985, *Kosmonavtika. Encyclopedia*, Moskva, Sovetskaja encyclopedia.

Greenberg R. and Brahic A., eds.: 1984, *Planetary Rings*, The University of Arizona Press, Tucson.

Grewing M., Praderie F., and Reinhard R., eds.: 1987, *Exploration of Halley's Comet*, Springer-Verlag, Berlin, Heidelberg, New York, London, Paris, Tokyo.

Hall R. C.: 1977, *Lunar Impact: A History of Project Ranger*, NASA **SP-4210**.

Hartmann W. K., and Raper O.: 1974, *The New Mars*, NASA **SP-337**.

Hunten D. M., Colin L., Donahue T. M., and Moroz V. I., eds.: 1983, *Venus*, The University of Arizona Press, Tucson, Arizona.

Kieffer H. H., Jakosky B. M., Snyder C. W. and Mattheus M. S., eds.: 1992, *Mars*, The University of Arizona Press, Tucson.

Kuzmin A. D. and Marov M. Ya.: 1974, *Physics of the planet Venus*, Moscow, Nauka, 1974 (in Russian).

(Lunar Prospector*) 1998, *Science* **281**, 1475–1500.

(Magellan*) 1992, *J. Geophys. Res.* **97**, No. E8, 13063–13689.

(Mariner 5*) 1974, *Science* **183**, 1289–1320.

(Mariner-9*) 1972, *Icarus* **17**, No. 2, 289–569.

(Mars 5*) 1975, *Kosmich. issled.*** **13**, 3–130.

(Mars Global Serveyor*) 1998, *Science* **279**, 1671–1698.

(Mars Pathfinder*) 1997, *Science* **278**, 1734–1774.

Moroz V. I.: 1978, *Physics of the planet Mars*, Moscow, Nauka (in Russian).

Moroz V. I.: 2001, 'Spectra and spacecraft', *Planetary and Space Science* **49**, 173–190.

Morrison D., ed.: 1982, *Satellites of Jupiter*, The University of Arizona Press, Tucson.

(NEAR*) 2000, *Science* **289**, 2085–2101; 2001, *Science* **292**, 484–491.

Perminov, V. G.: 1999, *The difficult road to Mars. A brief history of Mars exploration in the Soviet Union*. NASA **NP-1999-251-HQ**.

(Pioneer Venus*) 1980, *J. Geophys. Res.*, **85**, No. A13, 7575–8337.

(Phobos*) 1989, *Nature* **341**, No. 6243, 581–618, and 1991, *Planetary Sp.Sci*. **39**, No. 1/2, 1–399.

Reinhardt R., ed.: 1986, *Space missions to Halley's Comet*, ESA **SP-1066**.

Sagdeev R. Z.: 1994, *The making of the Soviet scientist*, John Wiley, New York, Chichester, Brisbane, Toronto, and Singapore.

Sagdeev R. Z., Blamont J., Galeev A. A., Moroz V. I., Shapiro V. D., Shevchenko V. I., and Szego K.: 1986, 'Vega spacecraft encounters with comet Halley', *Nature*, **321**, 259–262.

Sagdeev R. Z., Zakharov A. V.: 1989, 'Brief history of the Phobos mission', *Nature* **341**, 518–618.

Semenov Yu. P., ed.: 1996, *Raketno-kosmicheckaya korporatsiya 'Energiya' imeni S.P. Koroleva*, RKK 'Energiya' (in Russian).

Siddiqi A. A.: 2000, *Challenge to Apollo: the Soviet Union and the space race, 1945–1974*, NASA **SP 2000–4408**.

Serebrennikov, V. A., Voitik V. L. and Shevalev I. L. *et al.*, eds.: 1997, *NPO imeni S.A. Lavochkina. Na zemle, v nebe i v kosmose*, Moskva, Voennyi parad (in Russian).

Siddiqi A. A.: 2002, *Deep Space Chronicle: A Chronology of Deep Space and Planetary Probes, 1958–2000*, NASA **SP-2002-4524**.

Sidorenko, A. V. ed.: 1980, *Poverkhnost Marsa*, Moscow, Nauka.

Snyder C. W. and Moroz V. I.: 1992 'Spacecraft exploration of Mars', *Mars* (H. H. Kieffer, B. M. Jakosky, C. W. Snyder and M. S. Mattheus eds.) The University of Arizona Press, Tucson.

Spitzer C. R., ed.: 1980, *Viking Orbiter Views of Mars*, NASA **SP-441**.

(Vega 1 and 2*) 1987, *Kosmich. issled.*** **25**, No. 5 and 6, 643–958.

(Vega and Giotto, Halley comet flyby) 1986, *Nature* **321**, 259–366.

(Vega balloons*)1986, *Science* **231**, 1349–1425.

(Venera 9 and 10*) 1976, *Kosmich. issled.*** **14**, No. 5 and 6, 651–877.

(Venera 11 and 12*) 1979, *Kosmich. issled.*** **17**, No. 5, 829.

(Venera 13 and 14*) 1983, *Kosmich. issled.*** **21**, No. 2, 147–319.

(Venera 15 and 16*) 1985, *Kosmich. issled.*** **23**, No. 2, 179–267.

(Viking 1 and 2*) 1977, *J. Geophys. Res.* **82**, No. 28, 4249–4681 and 1979, *J. Geophys. Res.* **84**, No. B14, 7909–8519.

Vinogradov, A. P. ed.: 1971, *Peredvizhnaia laboratoria na Lune 'Lunokhod-1'*, Moscow, Nauka.

Vinogradov, A. P. ed.: 1974, *Lunnyi grunt iz Morja Izobiliia*, Moskva, Nauka.

Vinogradov A. P., ed.: 1975, 'Cosmochemistry of Moon and planets', *Proceedings of US-Soviet conference*, Moscow, Nauka (in Russian).

Von Braun W. and F. I. Ordway III.: 1969: *History of rocketry and space travel*, Thomas Y. Crowell Company, New York.

(Voyager 1*) Jupiter: 1979, *Science* **204**, 945–1008; Saturn: 1981, *Science* **212**, 159–423.

(Voyager 2*) Jupiter: 1980, *Science* **206**, 925–996; Saturn: 1982, *Science* **215**, 499–594; Uranus: 1986, *Science* **233**, 39–109; Neptune: 1989, *Science* **246**, 1417–1501.

Wilford J. N.: 1969, *We reach the Moon*, Bantam Books, New York, Toronto, London.

*A special issue or set of publications in a single issue.

**An English translation of *Kosmicheskie issledovaniia* is available as *Cosmic Research.*