Spaceflight: The Development of Science, Surveillance, and Commerce in Space

This paper provides a comprehensive retrospective of the scientific and human aspects of spaceflight as well as the commercial activities, security considerations, and the potential future options for exploration and development in space.

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ABSTRACT | To commemorate the centennial of the Proceedings of the IEEE, several authors from diverse areas of expertise examine space exploration from its beginnings in the middle of the last century and look onward to half a century in the future. Beginning by examining the reasons why the two 20th century superpowers believed that space exploration was an important investment, the chronological review of early developments includes discussions on science, commerce, and national security; the evolution of space-related technologies; progress and advancements in launch vehicles, spacecraft, and spacecraft payloads; and improvements in space communications and tracking. With the subjects of robotic solar system exploration and crewed missions to space discussed in some detail, the great advances of the last 60 years establish a foundation for addressing the challenges of future human flight beyond Earth's vicinity—challenges that are technical, political, social, and economic in nature. The authors take a pragmatic view in making forecasts for the future of spaceflight: they limit their conjecture, for the most part, to the next 50 years. While it is very difficult to make realistic predictions for longer periods, the authors are confident that space exploration continues to grasp the public's imagination and desire to know more about the universe, and that it continues to build on many of the same questions that inspired the space program in the mid-20th century.

KEYWORDS | Cold War; communications satellites; earth science; human presence in space; lunar science; national security; navigation and positioning; remote sensing; solar science; solar system; spaceflight

I. INTRODUCTION (Roger D. Launius)

Efforts in space emerged in large part because of the pressures of national security during the Cold War between the United States and the Soviet Union. From the latter 1940s, the U.S. Department of Defense (DoD) and the Soviet Union's military pursued research in rocketry and upper atmospheric sciences as a means of assuring their national leadership in this critically important dual-use technology. Over time additional nations entered the military, commercial, scientific, and human space community and engaged in a broad-based

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set of activities that has transformed human society in the more than 50 years that these efforts have been underway.

The civilian side of the space effort really began in 1952 when the International Council of Scientific Unions established a committee to arrange an International Geophysical Year (IGY) for the period July 1, 1957 to December 31, 1958. After years of preparation, on July 29, 1955, the U.S. scientific community persuaded President Dwight D. Eisenhower to approve a plan to orbit a scientific satellite as part of the IGY effort. The Soviet Union agreed to launch a scientific satellite as part of the IGY effort as well. With the launch of Sputnik 1 and 2 by the Soviet Union in the fall of 1957 and the American orbiting of Explorer 1 in January 1958, the space race commenced and did not abate until the end of the Cold War—although there were lulls in the competition. The most visible part of this competition was the human spaceflight program—with the Moon landings by Apollo astronauts as *de rigueur*—but the effort also entailed robotic missions to several planets of the Solar System, military and commercial satellite activities, and other scientific and technological labors.

In the post-Cold War era the space agenda underwent significant restructuring and led to an expansion of such cooperative ventures as the International Space Station (ISS) and the development of launchers, science missions, and applications satellites through international consortia. It has also led to a broadening of actors as many nations now have the capability to reach into space and to undertake complex scientific, commercial, national security, and other activities there. This overview will examine the historical background of space exploration, focusing on its history and evolution in the last 50 years with commentary on possible futures.

II. SCIENTIFIC EXPLORATIONS IN THE SPACE AGE (Roger D. Launius)

From the 1960s to the present, for some, space has represented national prestige on the world stage and pride at home. That outlook drove both the United States and the Soviet Union in the first years after Sputnik to pursue aggressive space science missions. But this competition also fueled efforts to understand the nature of the universe as never before. Although space science went back to the early 20th century and advanced significantly during and after World War II (with the development of German V-2 rocketry, for example, Fig. 1), the history of space science really began in 1957 when the first artificial satellites were launched as part of the IGY.

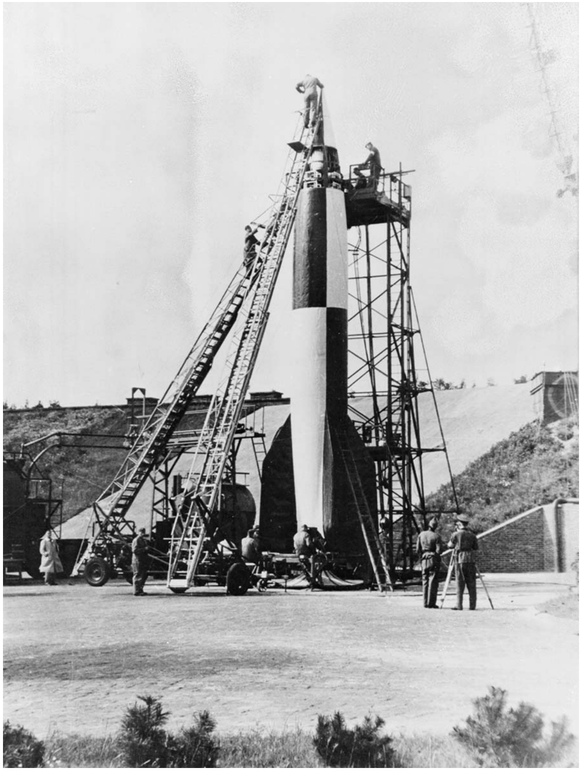

Fig. 1. ***The German Army prepares a V-2 for a test launch. (NASA photograph.)***

The Soviet Union launched Sputnik 1 on October 4, 1957, and utterly changed the nature of space science (Fig. 2). This satellite was the Soviet entry into the IGY program, and its success spelled crisis in the United States. Within weeks accelerated efforts for American spaceflight had been placed in motion. To catch up, on January 31, 1958, the United States placed the first American satellite Explorer 1 into orbit. This satellite discovered what came to be known as the Van Allen Radiation Belts, later confirmed by additional Explorer spacecraft.

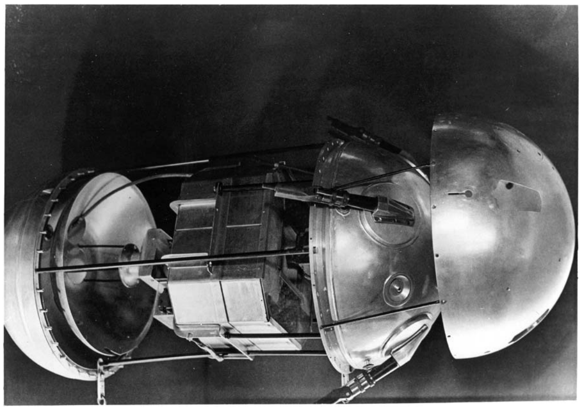

Fig. 2. ***This exploded view of Sputnik 1 shows the inner parts of the Sputnik spacecraft. (NASA photograph.)***

A. Lunar Science (Roger D. Launius)

With the conclusion of the IGY, the United States went head-to-head with the Soviet Union in a robotic race to the Moon—and lost. The Moon was an early target for both the United States and the Soviet Union because it was comparatively close; there were also numerous opportunities every month for a launch to the Moon and it would be a significant public relations coup in the international community for the nation reaching it first.

After some false starts in fall 1958, the Soviet Union succeeded in launching several successful lunar probes in no small measure because it had built large rockets with significant payload capacity, something not yet developed in the United States. In January 1959, the Soviets sent Luna 1 past the Moon and into orbit around the Sun, following up with Luna 3 to transmit pictures of the far side of the Moon—thereby giving the Soviets an important "first" in lunar exploration. Meanwhile, in March 1959, Pioneer 5 finally flew past the Moon, much too late to assuage America's loss of pride and prestige. Thus ended the first phase of lunar exploration, with the Soviet Union a clear winner.

In December 1959, after the failure of the first lunar probes, the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) started the Ranger project, and on August 30, 1961, NASA launched the first Ranger, but the launch vehicle placed it in the wrong orbit. Two more attempts in 1961 failed, as did two more attempts in 1962. NASA then reorganized the Ranger project and did not try to launch again until 1964. By this time its engineers had eliminated all the scientific instruments except a television camera. Ranger's sole remaining objective was to go out in a blaze of glory as it crashed into the Moon while taking high-resolution pictures. Finally, on July 31, 1964, Ranger 7 worked and transmitted 4316 beautiful, high-resolution pictures of the lunar Sea of Clouds. Rangers 8 and 9 also worked well.

Other projects by the United States followed, especially the Surveyor soft-landers on the Moon and the Lunar Orbiter mapping mission (Fig. 3). Ultimately these lunar satellite exploration programs succeeded in providing data useful to the scientific community and information about the Moon useful to those planning the Apollo landings, but only after significant missteps and false starts and considerable investment by the nation. In so doing, the United States finally eclipsed the early successes of the Soviet Union in sending probes to the Moon.

Throughout the 1960s and early 1970s when the United States was undertaking its accelerated efforts to explore the Moon, the Soviet program also had 20 successful missions there and achieved several notable firsts: first probe to impact the Moon, first flyby and image of the lunar farside, first soft-landing, first lunar orbiter, and first circumlunar probe to return to Earth. The two successful series of Soviet probes were the Luna (15 missions) and the Zond (five missions). Lunar flyby missions (Luna 3; Zond 3, 6, 7, and 8) obtained photographs of the lunar surface, particularly the limb (southern) and farside regions. The Zond 6, 7, and 8 missions circled the Moon and returned to Earth, where they were recovered (Zond 6 and 7 in Siberia, and Zond 8 in the Indian Ocean). Three robotic missions (Luna 16, 20, and 24) also soft-landed and returned lunar samples to Earth. Between the end of the Apollo program in December 1972 and the return of Luna 24 in August 1976, the Soviets had the Moon to itself and flew three more successful missions during this period.

In spring 1994, the United States returned to the Moon for the first time since Apollo. Clementine was a joint project between the U.S. DoD's Strategic Defense Initiative Organization and NASA. Its objective was to test sensors and spacecraft components under extended exposure to the space environment and to make scientific observations of the Moon. The observations included imaging at various wavelengths, including ultraviolet and infrared, laser ranging altimetry, and charged particle measurements. Lunar mapping took approximately two months, but as the mission was beginning a new phase in May 1994, the spacecraft malfunctioned. In spite of this, Clementine mapped more than 90% of the lunar surface. Scientists found that data returned by Clementine showed ice at the Moon's South Pole. The prospect of ice on the lunar surface reenergized lunar science.

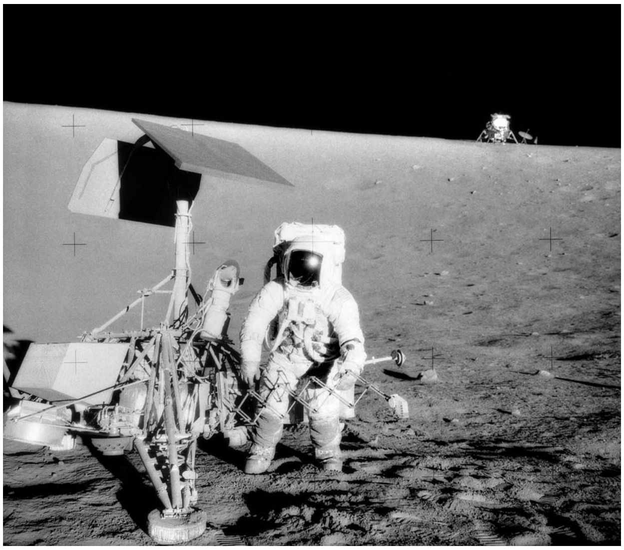

Fig. 3. ***Charles Conrad Jr., Apollo 12 Commander, examines the unmanned Surveyor III spacecraft during the second extravehicular activity (EVA-2). The Lunar Module (LM) "Intrepid" is in the right background. This picture was taken by astronaut Alan L. Bean, Lunar Module pilot. Apollo 12 landed on the Moon's Ocean of Storms only 200 m from Surveyor III. The television camera and several other components were taken from Surveyor III and brought back to Earth for scientific analysis. Surveyor III soft-landed on the Moon on April 19, 1967. (NASA photograph.)***

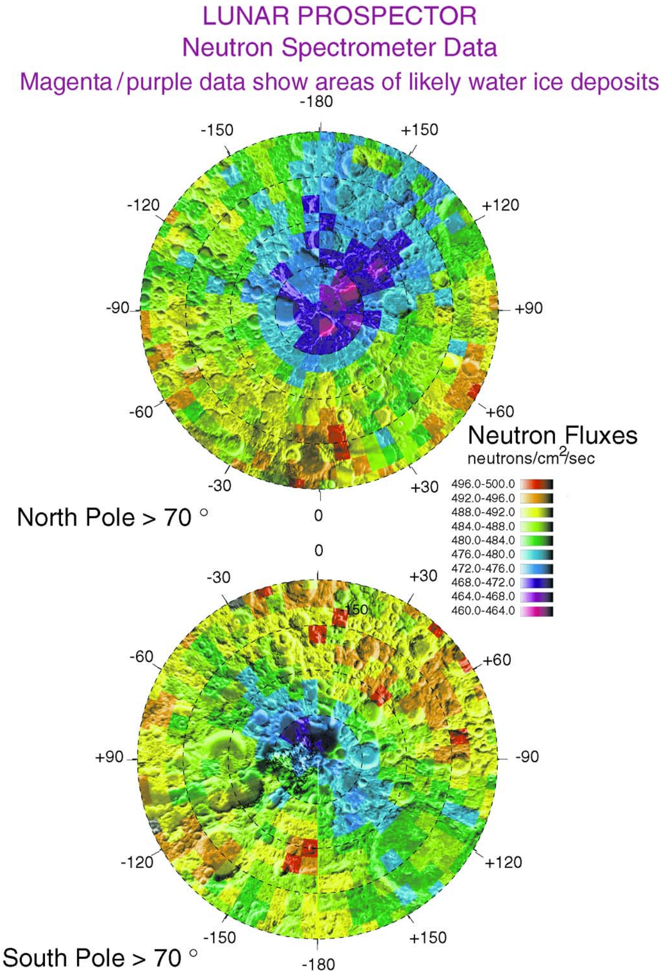

Fig. 4. ***The neutron spectrometer instrument aboard Lunar Prospector was intended to detect hydrogen to a depth of 0.5 m. The medium energy neutron counts from the spectrometer suggested that at the two poles water ice might exist. These polar maps clearly reveal an increasing definition of the target areas—with likely water deposits. The North Pole region, in particular, showed evidence of water deposits in permanently shadowed craters, the darker colored areas. (NASA photograph.)***

Excitement over this discovery spurred development of Lunar Prospector, a small probe that would "prospect" the lunar crust and atmosphere for minerals, water ice, and certain gases; map the Moon's gravitational and magnetic fields; and learn more about the size and content of the Moon's core. Launched on January 6, 1998, Lunar Prospector began its short-term mission to globally map the Moon. Lunar Prospector's most significant discovery, announced on March 5, 1998, was confirmation that as much as 300 billion kilograms of water ice was scattered inside the craters of the lunar poles (Fig. 4). To many scientists' surprise, Lunar Prospector detected nearly 50% more water ice in the North than in the South. From these data, mission scientists also inferred that ice crystals might be dispersed over a large surface area: 5000–20 000 km^2 at the South Pole and 10 000–50 000 km^2 at the North Pole. This discovery portended enormous consequences since humans might use it to "live off the land" on the Moon. Hydrogen could be used to produce rocket fuel and generate electricity, while oxygen could be breathed. Water, of course, could be consumed and used for a variety of other purposes. This finding suddenly made human colonization of the Moon seem possible.

More recently, the Lunar Reconnaissance Orbiter (LRO), launched in 2009, was specifically designed to determine the extent of water on the Moon. It had an impactor aboard, Lunar Crater Observation and Sensing Satellite (LCROSS), that directly hit one of the permanently shadowed regions near the Moon's pole to create a crater, throwing tons of debris and potentially water ice and vapor above the lunar surface. As it did so, the LRO flew through it taking measurements of hydrated minerals demonstrating that water existed on the Moon.

At the same time, two other missions to the Moon yielded important results. First, Chandrayaan-1, India's first mission to Moon, was launched successfully on

Fig. 5. ***This montage of the planets and four large moons of Jupiter in this solar system are set against a false-color view of the Rosette Nebula. The light emitted from the Rosette Nebula results from the presence of hydrogen (red), oxygen (green), and sulfur (blue). Most of the planetary images in this montage were obtained by NASA's planetary missions, which have dramatically changed the human understanding of the solar system in the past 50 years. (NASA illustration.)***

October 22, 2008, from the Satish Dhawan Space Centre (SHAR), Sriharikota, India. The spacecraft orbited the Moon at 100 km above the lunar surface to undertake chemical, mineralogical, and photogeologic mapping. The spacecraft was truly a transnational effort; it carried 11 scientific instruments built in India, the United States, the United Kingdom, Germany, Sweden, and Bulgaria. The Japan Aerospace Exploration Agency (JAXA) has also undertaken the Kaguya mission, an orbiter at 100-km altitude and two small satellites (Relay Satellite and VRAD Satellite) in polar orbit. Launched on September 14, 2007, from the Tanegashima Space Center in Japan, its mission was to explore the evolution of the Moon. Scientific instruments undertook a global map of lunar surface (including the far side), magnetic field measurements, and gravity field measurement.

B. Planetary Science (Erik M. Conway)

Interest in going to the planets existed in Western culture long before the advent of the space age. Science fiction writers and even some scientists speculated about extraterrestrial life and the possibility that aliens might come to Earth, and early space age visionaries like Werner von Braun thought about how to get Earthlings to Mars (Fig. 5). The idea that humans would have to go to other planets to explore has sometimes been called the Von Braun paradigm, but originates with Jules Verne. In Verne's era, remote control of a vehicle, let alone the more recent development of autonomous vehicles, was inconceivable. But to date, only exploring machines have gone to other planets. The advent of wireless telecommunications and, in particular, the establishment of NASA's Deep Space Network (DSN) has made this possible.

The first planetary mission to successfully return telemetry from the vicinity of its planetary target was the U.S. Mariner 2 mission to Venus in 1962. Built from a modified Ranger lunar impact spacecraft by JPL, it hosted microwave and infrared radiometers, a magnetometer, and plasma and charged particle sensors on a short "flyby" mission. It was followed by a series of probes by both the Soviet Union and the United States during the 1960s. The Soviet Union also began trying to land on Venus, finally succeeding with Venera 7 in December 1970. The Soviet Union sent several more landers to Venus, and also carried out a pair of Vega balloon missions to Venus in collaboration with France in 1985.

Mars was the next target of the race to explore the Solar System. The first successful mission to Mars, Mariner 4, cruised by the planet in July 1965, returning 21 shocking photos of a crater-pocked landscape (Fig. 6). A Soviet lander reached the surface in 1971 but failed 20 seconds later; both the United States and the Soviet Union succeeded in placing spacecraft in Mars orbit that year. The U.S. Viking landers reached the surface in 1976, returning years of data and thousands of television images.

The final U.S. Mariner mission was also the first spacecraft to visit the innermost planet Mercury. After a gravity assist from Venus in February 1974, Mariner 10 conducted three flybys of Mercury between March 1974 and March 1975. More than 30 years elapsed before Mercury received another robotic visitor. In 2011, the NASA MESSENGER mission went into orbit for what was

Fig. 6. ***This image of Mariner 4 superimposed on an image of Mars was used to advertise the 1965 mission. (NASA illustration.)***

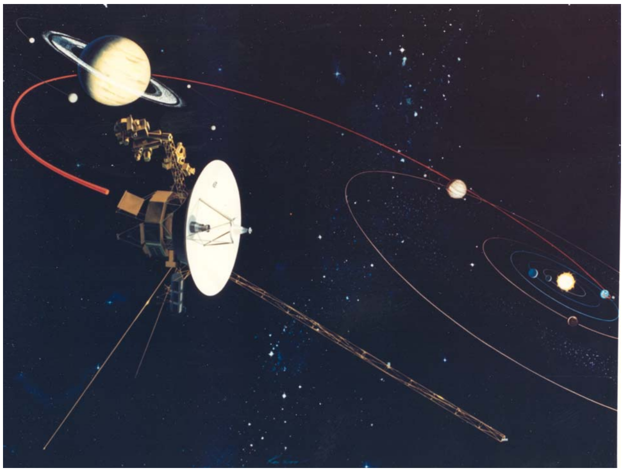

Fig. 7. ***This NASA artist's conception shows the Voyager spacecraft as it travels outward from Earth on its outer planetary tour. (NASA illustration.)***

originally planned to be a one-year mission but which has been extended.

NASA Ames Research Center's Pioneer 10 was the first spacecraft to explore one of the outer planets. It flew by Jupiter in 1973; its twin, Pioneer 11, conducted flybys of Jupiter in 1974 and Saturn in 1979. Radiation data from the two led to design changes in the next outer planet spacecraft being built, JPL's Voyagers. Launched in 1977, the two Voyager missions were aimed at completing a Grand Tour of all four of the gas giants of our Solar System (Fig. 7). Voyager 1 reached Jupiter in 1979 and Saturn in 1980. Voyager 2, which did flybys of all four planets, reached Uranus in 1986 and Neptune in 1989. Both Voyagers are still operating and have passed through the solar wind termination shock into a transition region separating plasma of solar origin from the interstellar medium.

The first two decades of planetary exploration were entirely a U.S./Soviet Union affair, but 1985 witnessed the arrival of two new players. Japan and the European Space Agency (ESA) each launched spacecraft to rendezvous with Halley's Comet in March 1986. Japan's Suisei performed a distant flyby, while ESA's Giotto, which was armored against particle impacts, passed within 600 km of the comet's nucleus. The same decade saw a severe decline in the rate of planetary exploration by the United States, which launched no new planetary missions between 1979 and 1988.

The Voyager flybys of Jupiter and Saturn were eventually followed by two orbiting missions. The Jupiter mission, NASA's Galileo, orbited Jupiter for nearly eight years, providing information about the gas giant and the Galilean moons. This spacecraft also carried an atmosphere probe that made its descent into Jupiter December 7, 1995, and returned about 57 min of data before being crushed. The Saturn mission was a joint NASA/ESA enterprise called Cassini/Huygens. The JPL-built Cassini orbiter carried the ESA probe Huygens to Saturn, and released Huygens toward the moon Titan in December 2004. The probe reached Titan's surface January 14, 2005, returning about 90 min of data and several intriguing images (Fig. 8). The Cassini orbiter discovered water-rich cryovolcanic plumes on Saturn's moon Enceladus. The still-functioning Cassini is expected to end its mission in 2017.

During the 1990s, the rapid evolution of powerful, compact microprocessors enabled new capabilities. While the Soviet Lunokhod Moon rovers of the 1970s were the first mobile surface robots, they were driven from Earth

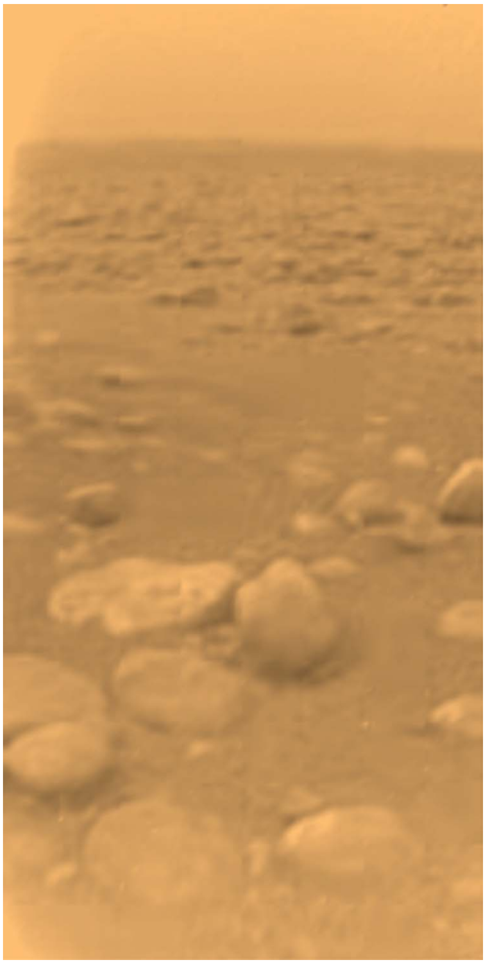

Fig. 8. ***This image of the surface of Titan was taken by the European Space Agency's Huygens probe when it touched down. First images released by ESA depict sinuous drainage channels leading to an apparent shoreline. What is draining? Possibly liquid methane. The orange landscape around the Huygens landing site is littered with little rocks, rounded and smooth like river rocks on Earth. One of the images seems to show tendrils of ground fog made not of water but perhaps ethane or methane. (ESA photograph.)***

telerobotically. The 1997 Mars Pathfinder mission's tiny Sojourner rover introduced very limited autonomy to surface mobility; the 2003 Mars Exploration Rovers introduced more. Autonomous in-space navigation software demonstrated by the Deep Space 1 mission allowed the 2005 Deep Impact mission to hit comet Tempel 1 with a self-guided impactor. The Mars Science Laboratory, also known as Curiosity, is to be the largest Mars lander yet; and it is to execute, in August 2012, the most precise landing yet on the surface of Mars.

The former Soviet Union's principal successor state, Russia, has tried twice to reach Mars since the Soviet Union's breakup without success. In 1996, there was an ambitious attempt to reach Mars with an orbiter and surface stations. In 2011, it launched a sample-return mission Phobos-Grunt to the Martian moon Phobos; however, the vehicle failed to escape Earth orbit.

ESA launched its first two planetary orbiters shortly after the start of the new century. Mars Express, launched in 2003 with a small lander named Beagle 2, reached Mars orbit successfully in 2004, while Beagle 2's landing failed. Venus Express, launched in 2005, operated in Venus orbit for more than five years.

The first return of samples from an asteroid was achieved by the Japanese spacecraft Hayabusa. This spacecraft launched in 2003, captured samples from the asteroid Itokawa in 2005, and returned with the samples to Earth in 2010. The first Japanese planetary orbiter Akatsuki arrived at Venus in 2010, but orbit insertion was unsuccessful.

Paralleling the evolution of planetary science missions has been the design, development, and operations of the Deep Space Network (DSN). This network, comprising antenna complexes in California, Spain, and Australia, plus a control center at JPL, has been a true enabler for deep space, as well as lunar missions of exploration (Fig. 9). Providing tracking, telemetry, and command services to these missions has enabled them to conduct activities that have evolved from real-time control through preprogrammed sequence-driven instructions and even to autonomous operations. Even more impressive is the fact that since the late 1950s, the performance level of these services in terms of data rates and tracking precision has grown by many orders of magnitude. During this same time interval, the distances spanned have grown from a few thousand kilometers to billions of kilometers, with consequent impacts on signal strength and round trip communications times. All of this has been accomplished by means of larger antennas, higher frequencies, more sensitive receivers, higher power transmitters, and better signal processing on Earth, along with similar developments on the spacecraft side of the link. The outlook for the DSN of the future may include not only very wideband radio links, but also optical links that can support data rates of gigabits per second from planetary distances. Moreover, deep space tracking will also see drastic improvements that may include autonomous navigation of probes that will explore the edge of our solar system and beyond.

Fig. 9. ***The 70-m antenna of the Canberra Deep Space Communications Complex, located outside Canberra, Australia. This complex is one of three that comprise NASA's Deep Space Network. The other complexes are located in Goldstone, CA, and Madrid, Spain. (NASA photograph.)***

One interesting coda on the history of planetary exploration was the 2006 decision by the International Astronomical Union to finally adopt a formal definition of "planet." The decision was driven by the discovery of objects larger than Pluto in the Kuiper Belt surrounding the Solar System. The discovery threatened to expand the number of planets in the Solar System into the dozens, if not hundreds. After a rancorous vote, the IAU defined these large Kuiper Belt objects, as well as Pluto itself and the (now-ex) asteroid Ceres as "dwarf planets." Two in-flight NASA missions, New Horizons to Pluto and Dawn to Vesta and Ceres, became the first two spacecraft aimed at this new class of celestial body (Fig. 10).

C. Earth Science (Erik M. Conway)

Earth science from space diversified much more quickly than did planetary exploration. After the first Soviet and U.S. scientific satellites Sputnik 2 and Explorer 1 were orbited, other nations quickly joined the race to explore Earth. The United States built a satellite to host British instruments, launched in April 1962. A Canadian built research satellite Alouette 1 followed later that year; an Italian satellite, San Marco A, in December 1964 followed by France in 1965, Japan and China in 1970, and India in 1975. Many of these early satellites were designed to explore the ionosphere, the Earth's magnetic field, and solar and cosmic radiation.

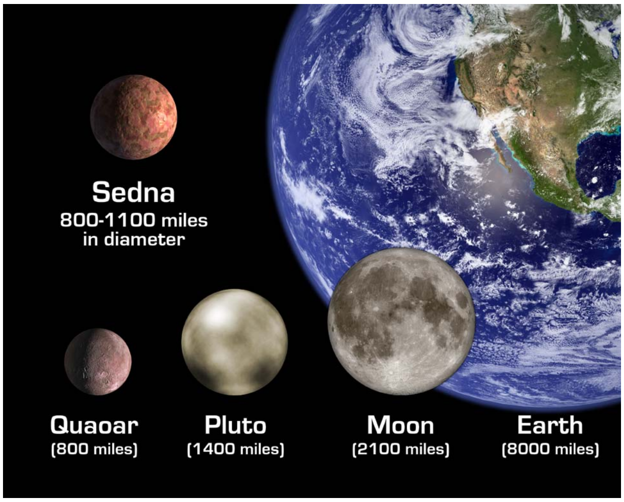

Fig. 10. ***The artist's rendition shows the newly discovered planet-like object, dubbed "Sedna," in relation to other bodies in the Solar System, including Earth and its Moon; Pluto; and Quaoar, a planetoid beyond Pluto that was until now the largest known object beyond Pluto. The diameter of Sedna is slightly smaller than Pluto's but likely somewhat larger than Quaoar. (NASA illustration.)***

Nations sponsored these missions as a means of developing their technological capabilities, supporting domestic scientific communities, and national pride. Another important component of national interest was military. Several countries flew research satellites as part of military space programs, including the United States, where the armed services originated space science. Military organizations had a variety of reasons for being interested in Earth science. Mapping the Earth's gravity field was important to accurate long-range ballistic missile targeting, for example. Armed services sought better weather forecasting, and needed to understand atmospheric radiation and radiative transfer for nuclear weapons detection, missile guidance systems, and telecommunications.

Weather satellites were an early focus of effort, with the first successful weather satellite TIROS launched by the United States in 1960. These satellites demonstrated both the scientific potential of space observations as well as the possibility of practical application. Weather satellites were expected to improve weather forecasting, and especially severe storm forecasting, and were quickly deployed by both civilian and military organizations in several countries. In NASA, an experimental weather satellite program called Nimbus developed atmospheric remote sensing capabilities in the microwave, ultraviolet, and infrared regimes, often by refining techniques already developed for astrophysics. These enabled research on the chemistry and dynamics of the upper atmosphere, as well as certain kinds of land remote sensing. The capabilities became policy relevant during the 1980s, when discovery of the Antarctic stratosphere's "ozone hole" produced movement toward international regulation of certain kinds of refrigerants (Fig. 11).

Oceanography began to also benefit from international interest in remote sensing during the 1970s. The U.S. Skylab space station carried physical oceanography experiments that were followed by an oceanographic satellite called Seasat A. While Seasat did not operate for long, it demonstrated the ability to measure winds at the ocean surface, very accurate sea surface heights, and the usefulness of synthetic aperture radar. Many years elapsed before Seasat's experiments were flown again, but all eventually were. A joint U.S./France mission TOPEX/Poseidon restarted sea surface height measurements, and was succeeded by a series of "Jason" satellites. Since the early 1990s, synthetic aperture radars flown aboard European and Canadian satellites have helped revolutionize study of the world's ice sheets.

As anthropogenic climate change became a major research topic in the 1990s; some climate-related, but previously underemphasized, research fields also began to draw more interest. The United States and France made large investments in aerosol and cloud studies during the period, fostering a veritable constellation of related satellites. Gravity studies also revived, with a joint U.S./Germany satellite pair (GRACE) demonstrating the ability to track mass loss from ice sheets and aquifer depletion via

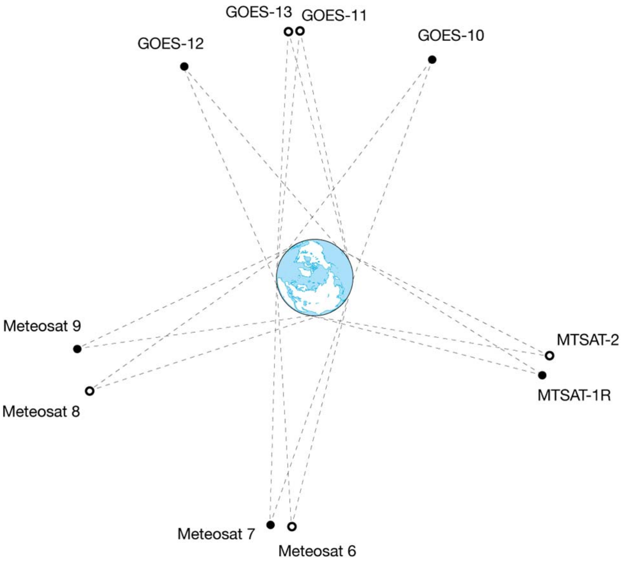

Fig. 11. ***This illustration shows the weather constellation of satellites in geosynchronous satellites in equatorial orbit. Solid circles indicate operational satellites, and hollow circles show orbiting spares. Each of these satellites is placed at a chosen longitude to observe a section of the globe. The GOES satellites are operated by the United States, Meteosats by European nations, and MTSATs by Japan. China, India, and Russia have also operated weather satellites in geostationary orbit. (NASM illustration.)***

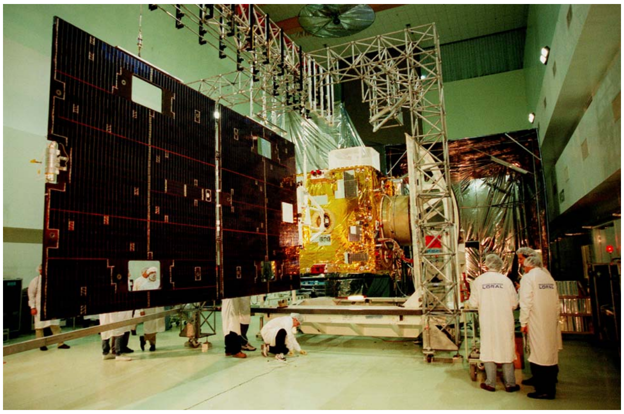

Fig. 12. ***The solar panels on the GOES-L weather satellite are fully deployed in this final test of the imaging system, instrumentation, communications, and power systems. The satellite was launched from Cape Canaveral Air Station (CCAS) aboard an Atlas II rocket in 1999. It was the fourth of a new advanced series of geostationary weather satellites for the NOAA. It is a three-axis inertially stabilized spacecraft that will provide pictures and perform atmospheric sounding at the same time. Once launched, the satellite was designated GOES-11 and provided backup capabilities for the existing, aging GOES East weather satellite. (NASA photograph.)***

changes in the Earth's gravity field. The same decade saw the addition of a few new national participants to Earth exploration, including Argentina and Brazil. One new mission, the joint U.S./Argentina SAC-D/Aquarius, will pioneer the ability to measure ocean salinity globally, a measurement desired to improve understanding of ocean circulation and the Earth's water cycle.

Earth exploration from space has been marked by extensive cooperation. When the United States initiated its weather satellite program, its leaders decided to give the data away to anyone, and everyone, who wanted it. That attitude has not been universal—there are pressures for privatization of weather and other sorts of data—but the cooperative spirit has led to many joint orbital missions, multinational field experiments supported by space agencies, and "foreign" instruments on "national" space assets. The NASA "A-Train" climate research satellite constellation contains instruments from Japan, Canada, Brazil, and France, and satellites from France and Japan have joined it to take advantage of synergy from overlapping measurements (Fig. 12).

D. Extrasolar Planets (Erik M. Conway)

One of the most exciting recent discoveries of the space age has been the confirmation that planets outside our own Solar System exist. A tentative detection in 1988 of a planet orbiting Gamma Cephei was not confirmed for many years, but in 1992, astronomers announced detection of a planet orbiting a pulsar. Pulsars are the remnants of exploded stars, so few astronomers had expected to find planets orbiting them, but the claim was quickly confirmed. Then, in 1995, the first planet in orbit around a star like our Sun was discovered, leading to a wave of such discoveries. By 2006, more than 200 had been identified. Initially these were referred to as extra-solar planets, but they are more commonly called exoplanets now.

This initial set of discoveries came entirely from ground-based observation, enabled by technological advancements in detectors and in data processing. These made it possible to detect the very small changes to a star's movement, or to its light output, as a planet orbits the star. They did not yet enable imaging of these exoplanets; instead, their existence was known only indirectly. Most of the early exoplanets were very large, gas giants like Neptune or Saturn, or an unexpected subclass of gas giants that astronomers decided to call "Hot Jupiters," because they were very close to their parent stars.

After 2006, two dedicated space-based planet-hunting missions joined the effort to expand knowledge of exoplanets. The French space agency CNES launched CoRoT in late December 2006. The CoRoT team announced discovery of its first exoplanet, a Hot Jupiter, in 2007. By 2011, CoRoT had found more than 400 exoplanet candidates. NASA's Kepler mission, launched in 2009, was designed to simultaneously observe more than 150 000 stars, to enable statistically valid claims to be made about the prevalence of planets, including Earth-sized ones, in the Milky Way. In February 2011, Kepler's science team released their first four months of data, proposing 1235 exoplanet candidates orbiting 997 host stars. Twenty four had been confirmed as of this writing. These were all in very short-period orbits compared to those in our Solar System; Kepler is only able to detect exoplanets with orbit periods as long as Earth's own after several years of watching.

By 2011, more than 600 exoplanets had been confirmed. The vast majority were gas giants of various descriptions, but some Earth- and so-called "super-Earth" sized planets were also known to exist. The initial Kepler data release suggested that these smaller bodies composed about 13% of exoplanets.

Astronomers have not yet confirmed the presence of an Earth-sized exoplanet within its star's "habitable zone," which they define as the region within which liquid water at the surface is possible. But a number of candidates exist in the Kepler data around stars that are smaller than our Sun, presenting the fascinating possibility of habitable exo-Earths in the Milky Way.

The next big question for exoplanet hunters is whether any of these bodies is actually Earth-like, not just in size and temperature but in composition. In particular, the question of whether any can support life can only be addressed by measuring the spectrum of an exoplanet's atmosphere. The infrared Spitzer Space Telescope has done this for a small number of very hot exoplanets, but is unable to see exoplanets of Earth's own temperature ranges. So confirming the existence of exo-Earths will have to await some future technological advancement.

E. Studying the Sun (Roger D. Launius and Andrew K. Johnston)

Throughout the globe astronomers and other scientists, as well as many amateurs, have turned their telescopes toward the Sun to learn about the Earth's nearest star. In addition, since the beginning of the space age scientists have dispatched numerous probes to investigate the features and effects of the Sun on Earth. The explosions (flares and coronal mass ejections) on the Sun fascinate us, and the highly energetic particles and billions of kilograms of very hot, electrified material expelled holds important ramifications for life on this planet. Indeed, sometimes this material takes a collision course with Earth and affects our orbiting satellites and electronics. As humanity becomes more dependent upon satellites in space we will increasingly feel the effects of space weather and need to predict it.

The magnetic emissions from the Sun are also critical to this planet, and how it interacts with the Earth's magnetosphere has a profound influence for us. The most famous effect from this interaction is the aurora in the polar latitudes that occurs when molecules in the upper atmosphere become excited by energetic electrons associated with these storms on the Sun. Additionally, when the Earth's environment is affected by activity from the Sun it causes geomagnetic storms and variations in the Earth's magnetic field.

Moreover, scientists who study the Sun have helped to chart the history of the Solar System, its origin and evolution, and are capable of predicting in a general sense what will happen to the Sun and the plants that orbit it in the distant future. With the Sun as a test subject, scientists have been able to resolve features and study physical processes in a way that is impossible with more distant stars and other astrophysical objects. Their work has determined that other stars also have spots, hot coronae, and magnetic activity. They also have learned how energy is released and particles are accelerated in the universe by studying these same processes on the Sun. Existing theories of particle physics are in part the result of these investigations.

Beginning at the start of the space age an extensive constellation of satellites have been dispatched toward the Sun to study solar properties and especially the Sun/Earth connection. Some of the satellites and observatories have a special mission to study the Sun at the height of the solar maximum, part of an 11-year cycle of activity. Some of the major satellites involved in this effort have included the following.

- Orbiting Solar Observatory (OSO): This series of eight NASA satellites built to study the Sun was launched between 1962 and 1975. Their primary mission was to observe an 11-year sun spot cycle in ultraviolet and X-ray spectra.
- Helios 1 and 2: Launched in 1974 and 1976, these probes, a joint project of NASA and the Federal Republic of Germany, entered a heliocentric orbit to study solar processes. Helios 2 holds the record for coming closest of any probe to the Sun.
- Solar Maximum Mission: This satellite was a pioneering mission in the field of solar science. It was launched in 1980 to study solar activity during the solar maximum and collected images and data for nine years.
- Geotail: Launched in 1992, it was designed and built by Japan's Institute of Space and Astronautical Science (ISAS). Geotail is a joint project with NASA, and it studies the Earth's magnetosphere to see how the solar wind and Earth interact.
- Yohkoh (Solar-A): An ISAS satellite launched in 1991, Yohkoh used X-ray instruments to collect data about the Sun over a period of nearly one solar cycle.
- Ulysses: Undertaking a polar orbit around the Sun, Ulysses completed its first orbit in 1994–1995 and continued thereafter to study high-latitude solar wind during solar maximum.
- Wind: Launched on November 1, 1994, by NASA, Wind explores the solar wind to help decipher its physical and chemical properties.
- The Solar and Heliospheric Observatory (SOHO): Launched in 1995, SOHO studied the Sun from its position near the L1 Lagrange point 1 500 000 km out in space.
- Polar: Launched on February 24, 1996, by NASA, this satellite made daily passes over Earth's North and South Poles to measure the energy and particles flowing into and out of the magnetosphere and producing the aurora.
- Advanced Composition Explorer (ACE): Launched on August 25, 1997, the primary purpose of ACE is to determine and compare the isotopic and elemental composition of several distinct samples of matter, including the solar corona, the interplanetary medium, the local interstellar medium, and Galactic matter.
- Transition Region and Coronal Explorer (TRACE): Launched in April 1998, this satellite gave scientists valuable information on magnetic field conditions in the photosphere, the transition region, and the corona during the upcoming solar maximum.
- Imager for Magnetopause-to-Aurora Global Exploration (IMAGE): Launched in March 2000, this satellite used neutral atom, ultraviolet, and radio imaging techniques to collect data about the magnetosphere during substorms and magnetic storms in the solar maximum.

- Cluster II: Four satellites launched July 16, 2000; these satellites measured the Earth's magnetic field by making simultaneous measurements. They enabled a 3-D study of the changes and processes taking place in near-Earth space.
- Genesis: Launched August 8, 2001, this spacecraft collected solar wind samples and returned them to Earth, but the recovery was faulty with the failure of the parachute system. Nonetheless, scientists recovered much of the data from the probe.
- Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI): Launched on February 5, 2002, RHESSI measures the energy released during a solar flare through a combination of high-resolution imaging in X-rays and gamma rays along with high-resolution spectroscopy. This approach enables researchers to find out where these particles are accelerated and to what energies. Such information is intended to advance understanding of the fundamental high-energy processes at the core of the solar flare problem.
- Solar TErrestrial RElations Observatory (STEREO): Launched on September 18, 2006, this spacecraft used two observatories—one ahead of Earth in its orbit and the other trailing behind—to study the structure and evolution of solar storms as they blast from the Sun and move out through space.
- Hinode (SOLAR-B): Launched on September 23, 2006, this was Japan's third solar observation satellite. It contained three onboard telescopes to study the Sun's eruptive phenomena and space weather, helping to predict the Sun's influence on the Earth.
- Time History of Events and Macroscale Interactions during Substorms mission (THEMIS): Launched in February 2007, five identical satellites line up once every four days along the equator and take observations synchronized with ground observatories of aurora phenomena.

F. Astronomy and Astrophysics (Roger D. Launius and Zse Chien Wang)

During the 1960s, space scientists began using space-based technology to enhance humanity's understanding of the universe beyond the Solar System. The traditional scientific field of astronomy underwent a tremendous burst of activity in the 1960s because of the ability to study the stars through new types of telescopes. In addition to greatly enhanced capabilities for observation in the visible light spectrum, NASA and other institutions supported the development of a wide range of X-ray, gamma ray, ultraviolet, infrared, microwave, cosmic ray, and radio astronomical projects. These efforts collectively informed the most systematic efforts yet to explain the origins and development of the universe.

The space age provided an opportunity to expand research far beyond the capabilities offered by ground-based observatories of earlier eras. Fundamental to this was the development of a series of Orbiting Astronomical Observatories (OAOs), first conceptualized not long after the birth of NASA. Two of these aluminum, octagonally shaped, solar-powered spacecraft were launched during the 1960s. The first failed less than two days into its mission because of a power system failure, but with the launch of OAO 2 on December 7, 1968, the potential of the program began to pay off as it provided an abundance of information on ultraviolet, gamma ray, X-ray, and infrared radiation, on the structure of stars, and on the distribution and density of matter in the interstellar environment. A series of six Orbiting Geophysical Observatories (OGOs) also contributed to this study, as well as to the study of the Solar System, by taking measurements of cosmic rays, particles, and fields in the interplanetary medium as well as radio emissions.

One of the exciting projects in this arena was X-ray astronomy. On June 12, 1962, the first rocket was launched using instruments to detect whether X-rays were present in any particular quadrants of the galaxy. It discovered a power source in the center. Calculations demonstrated that X-ray emissions from this source were ten times that of the Sun. In July 1963, another instrument package sent above the atmosphere took readings of the Crab Nebula and found intense X-ray activity emanating from it. In December 1970, the X-ray observatory Uhuru mapped about 85% of the sky, then located and measured the intensity of 161 X-ray sources. Many of these turned out to be black holes, a truly significant discovery of a segment of space where mass is so compressed and gravity so great that neither matter nor light can escape. Large amounts of X-rays, however, are emitted and can help explain much about the evolution of the universe.

By the early 1970s, satellite astronomy had helped to generate a major change in the larger field of astronomy and had reordered thinking on the subject. This occurred in spite of the fact that much of the research was built on the foundations laid by earlier astronomers. While space science did not make news in the 1980s, as the last decade of the 20th century dawned, NASA moved forward with its "Great Observatories" program and astounded the science world with its findings. The $2 billion Hubble Space Telescope was the first of these "Great Observatories," launched from the Space Shuttle in April 1990 (Fig. 13). A key component of it was a precision-ground 2.4-m primary mirror shaped to within 10 nm of perfection from ultralow expansion titanium silicate glass with an aluminum–magnesium fluoride coating. The first photos provided bright, crisp images against the black background of space, much clearer than pictures of the same target taken by ground-based telescopes. Controllers then began moving the telescope's mirrors to better focus images. Although the focus sharpened slightly, the best image still had a pinpoint of light encircled by a hazy ring or "halo."

At first many believed that the spherical aberration—a result of the mirror having the wrong shape—would cripple the 14-m-long telescope, and NASA received considerable negative publicity, but soon scientists found a way with computer enhancement to work around the abnormality. Because of the difficulties with the mirror, in December 1993, NASA launched the shuttle Endeavour on a repair mission to insert a new camera and corrective optics for the remaining instruments into the telescope and to service other instruments. During a week-long mission, astronauts conducted a record five spacewalks to repair the spacecraft. The first reports from the Hubble spacecraft indicated that the images being returned after this mission were more than an order of magnitude clearer than those obtained beforehand. For instance, as recently as 1980, astronomers had believed that an astronomical grouping known as R-136 was a single star, but the Hubble showed that it was made up of more than 60 of the youngest and heaviest stars ever viewed. The dense cluster, located within the Large Magellanic Cloud, was about 160 000 light years from Earth, roughly 10 trillion kilometers away.

Other "Great Observatories" followed. The Chandra X-Ray Observatory, launched on July 23, 1999, engaged in X-ray astronomy of the universe, concentrating on the remnants of exploded stars and even particles up to the last second before they fall into a black hole. More recently, the Compton Gamma-ray Observatory (launched April 5, 1991) and the Spitzer Space Telescope (SST) (launched August 25, 2003) observed the gamma-ray and infrared emissions, respectively, in the sky. Collectively, these "Great Observatories," led by the stunningly successful Hubble Space Telescope, have transformed our understanding of the cosmos.

Fig. 13. ***Attached to the "robot arm" the Hubble Space Telescope is unberthed and lifted up into the sunlight during the second Space Shuttle servicing mission designated HST SM-02 in 1997. (NASA photograph.)***

Very long baseline interferometry (VLBI), the use of widely spaced antennas in radio astronomy to achieve higher resolution images, has now become a space endeavor. The resolution of a radio interferometer improves with an increase in the "baseline" between the antennas. With one antenna on a spacecraft in Earth orbit, known as space VLBI, the baseline can far exceed that of a terrestrial interferometer. The first space VLBI satellite was HALCA, also known as Haruka, from Japan's ISAS (now part of JAXA). In 2011, Russia launched a space VLBI platform named RadioAstron.

G. Human Spaceflight (Matthew H. Hersch)

Mythologies surrounding the human exploration of space have been a part of both Western culture and other world traditions for thousands of years, with the act of flight to the heavens often associated with omnipotence and spiritual transformation. The possibility of employing rocket propulsion to hurl humans into space was a central motivation of the rocket pioneers of the early 20th century, many of whom courted military contracts in the hope of building spacecraft for human exploration of the heavens. The rich funding environment and technological innovations of World War II and the Cold War provided the means, after centuries of dreaming, to catapult humans into both Earth orbit and to Earth's nearest neighbor, the Moon. Funded at first as a pawn in superpower competition, human space exploration eventually became a permanent national infrastructure in both Russia and the United States, serving a variety of political, scientific, and social purposes.

While robotic craft have proven capable platforms for observation and communications, such craft were seldom the principal interest of early theorists, who eagerly absorbed science fiction about human voyages to distant worlds. In the absence of electronic sensing, data recording, and communications technologies, only vehicles carrying humans appeared likely to offer any practical benefit as exploration craft or weapons systems. Indeed, it was the possibility that liquid fuel rockets would be energetic enough to launch a piloted craft that had encouraged Russia's Konstantin Tsialkovsky, Germany's Hermann Oberth, and other pioneers to pursue theoretical study of liquid fuels and oxidizers, particularly cryogenic liquid hydrogen and liquid oxygen. Prior to the development of this technology, solid fuel rockets did not appear to be a particularly attractive propulsion technology for human flight, being simultaneously underpowered, unreliable, and unable to be throttled or extinguished once ignited.

The development of human spaceflight required both propulsion improvements and the creation of a variety of technologies to enable practical flight, particularly in the areas of guidance, navigation, and control. American physicist Robert Goddard, the Soviet Union's Sergei Korolev, and Germany's Wernher von Braun were among those principally responsible for demonstrating the feasibility of liquid-fuel rockets, though it was von Braun who achieved the greatest success in convincing governments to fund his work. After World War II, von Braun (having emigrated to the United States and working with the U.S. Army) and his Soviet counterpart Korolev advocated for the construction of piloted spacecraft, but appropriations for space projects remained scarce until nuclear weapons programs made surplus missile hardware available for exploration, and Cold War tensions made spaceflight a valuable tool for demonstrating national technical preeminence. While interest in the possibility of space travel existed in a variety of countries in the postwar period, the huge sums required for such experiments eventually limited human spaceflight research to the two superpowers.

While the liquid-fuel rocket had, by the late 1940s, emerged as the only transportation technology capable of propelling humans into space, debate remained as to the nature of the craft that would fly atop it. The U.S. Air Force contemplated the construction both of winged space planes and rudimentary piloted capsules. The U.S. Air Force's preferred means of achieving orbital flight was a hypersonic rocket aircraft (eventually begun as the X-20 "Dyna-Soar") that would be controlled by human pilot and carry a variety of reconnaissance and other payloads into space before reentering the Earth's atmosphere and landing on a conventional runway. A smaller capsule, though, might be launched more quickly and cheaply. Such a craft would provide little mass and volume allowance for instrumentation, camera equipment, or weapons. The principal roles of the vehicle would be to achieve a propaganda victory and demonstrate the capacity of human beings to survive in orbit (Fig. 14).

Though the U.S. Air Force and the National Advisory Committee for Aeronautics (NACA) made substantial inroads in the creation of both vehicles, the Soviet launch of Sputnik further complicated these plans, forcing the U.S. Air Force (and, upon its establishment in 1958, NASA) to contemplate a crash program to orbit an American pilot in a capsule, eventually canceling the Dyna-Soar program. While the U.S. DoD continued to fund human spaceflight projects throughout the 1960s (including the proposed Manned Orbiting Laboratory), technological innovations obviated the need for piloted space platforms for most military space applications, especially photographic reconnaissance. Meanwhile, Korolev, the principal Soviet rocket designer, cagily leveraged Soviet defense needs with his own desires to produce a spacecraft, the Zenit/Vostok, that could be pressed into service as either as a pilotless reconnaissance vehicle or a piloted craft. Despite these preparations, human spaceflight remained controversial in political and scientific quarters, with many American scientists fearing that such a project would cannibalize funds from more productive scientific pursuits. Ultimately, concerns about technical competitiveness trumped those of fiscal responsibility, and American and Soviet efforts to prepare a piloted spacecraft moved roughly in tandem through 1959 and 1960.

Both the United States and the Soviet Union recruited military aviators for their space programs, though in the United States, selections emphasized more experienced test pilots with advanced engineering training who might contribute materially to the design and evaluation of their vehicles. In other respects, the Soviet Vostok program and NASA's Project Mercury eventually employed similar technologies: a surplus ballistic missile lifting a capsule that, once in orbit, would sustain a human occupant for a day or more, a rudimentary solid fuel rocket engine to de-orbit the craft, an ablative heat shield to absorb the thermal energy produced as the craft returned through Earth's atmosphere, and a parachute system to break the craft's descent. With a large naval force, the United States planned to recover their astronauts at sea; the orbital inclination of the Soviet craft and the lack of a large Soviet

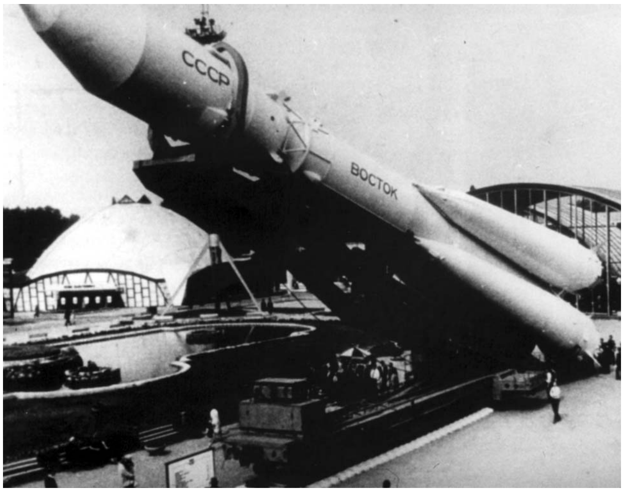

Fig. 14. ***Soviet Chief Designer Sergei Korolev was the godfather of the R-7, the world's first intercontinental ballistic missile (ICBM). A version of the R-7 launched Sputnik 1 on October 4, 1957, and Yuri Gagarin on April 12, 1961. The R-7 with its requirement for an enormous launch pad, a complex assembly sequence, elaborate launch procedures, cryogenic fuels, and radio-controlled guidance system made it an impractical weapon but it won favor as a fine space access launcher for the early Soviet space program. In addition, the R-7's warhead was so heavy that the missile had a range of only about 5600 km, hardly enough to reach the northern United States from the Soviet Union. As a result, it would be deployed as a weapon at only eight launch pads in Tyuratam and Plesetsk, in the northern Soviet Union. This image shows the R-7 on its rail system as it deploys for a test launch. (NASA photograph.)***

Fig. 15. ***The Launch of Freedom 7 on May 5, 1961 was the first American suborbital spaceflight of an astronaut. Aboard is Alan B. Shepard as the Mercury-Redstone (MR-3) rocket is launched from Pad 5, at what would become the Kennedy Space Center in Florida. (NASA photograph.)***

surface fleet would require a midair ejection for their cosmonauts and a perilous ground landing for their craft.

The Soviet Union's successful orbiting of Yuri Gagarin in 1961 (months before the flight of his American counterpart) gave that nation a second critical public relations victory. Gagarin's flight, though, also ensured an aggressive American effort to match Soviet achievements. Emboldened by the brief suborbital flight of the first American astronaut Alan Shepard in 1961 (and wary of the perceived Soviet lead in space technology; Fig. 15), President John F. Kennedy challenged Americans later that year to "land a man on the Moon and return him safely to Earth" by 1970. Though described by Kennedy as a move necessary to secure the safety of the free world, the proposal was, in actuality, a publicity ploy intended to embarrass the Soviet Union with a dramatic program well beyond the capabilities of either nation, thereby demonstrating American resolve to match Soviet technical achievements.

The historical record suggests that the Kennedy White House was ambivalent about the lunar goal almost immediately, and especially wary of the expense a lunar exploration program would require (Fig. 16). At the time of the announcement, NASA possessed neither a lunar spacecraft nor a launch vehicle capable of carrying it, and computing technologies required for translunar guidance and navigation remained notional. Astronauts landing upon the Moon would need to exit their spacecraft, though a pressure suit capable of withstanding the vacuum, extreme temperatures, and micrometeorite dangers of the space environment had yet to be invented. And the landing of a craft upon the Moon and its return required restartable rocket engines that would operate effectively in space.

Emboldened by President Kennedy's challenge, NASA quickly fixed certain key elements of the design for what would be known as Project Apollo. They included a conical Command Module in which three astronauts would venture to the vicinity of the Moon and return, and the Saturn launch vehicles that would carry them, designed at NASA's Marshall Spaceflight Center in Huntsville, AL, by engineers under von Braun. In an effort to minimize the size of the launch vehicle required, astronauts would use a technique called lunar orbit rendezvous (LOR), deploying a small landing craft from lunar orbit containing two of the three crewmembers that touched down on the lunar surface. While reducing the size of the landing craft, the technique required two spacecraft to rendezvous and dock hundreds of thousands of kilometers from Earth, a challenging maneuver with which neither NASA nor its Soviet counterpart had any familiarity. Despite the inherent dangers, LOR was adopted by both NASA and, eventually, by its Soviet rival.

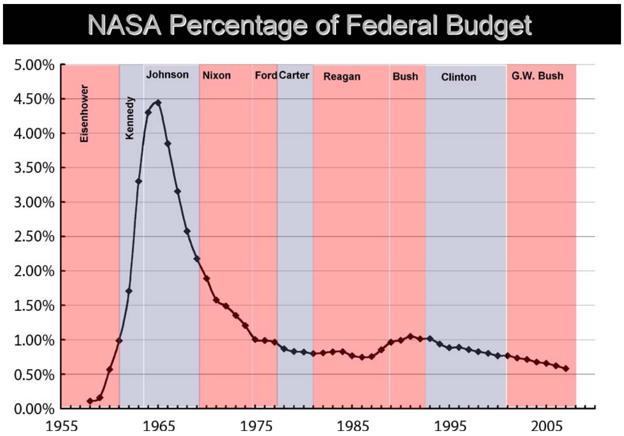

Fig. 16. ***This graphic shows the NASA budget as a percentage of the total federal budget. The 4.4% amount shown in the middle part of the 1960s was the investment that made possible the Moon landings of Project Apollo. Since the early 1970s this budget has stabilized at between 0.5% and 1% of the federal budget each year. That represents the level of investment in this activity that the U.S. citizenry has agreed to make in spaceflight, and any effort to increase it significantly will require the convergence of a set of factors that will raise the effort's importance among the public. (NASM illustration.)***

An aggressive Soviet design and launch effort during 1962–1965 enabled its cosmonauts to achieve several additional milestones, including the orbiting of the first woman, the first near-simultaneous space launches, and the first multicrewed flight and first spacewalk in a modified Vostok craft designated Voskhod. Though spectacular, these achievements belied a lack of organization in the Soviet program and a tendency to promote inexpensive stunts over projects with greater growth potential. Subsequent efforts by President Kennedy to abandon the Moon effort or invite Soviet participation received little support in Congress or among the Soviets, who feared disclosing the comparatively rudimentary state of their technology, and who undertook an unacknowledged crash program to match the American lunar effort. This effort ultimately produced the Soviet Soyuz craft, with orbital maneuvering and navigational capabilities lacking in previous Soviet craft.

During 1965 and 1966, the two-man American Project Gemini crews both matched Soviet achievements and mastered a series of technological challenges with which the Soviets had struggled, including extravehicular activity, rendezvous and docking, and long-duration flight (Fig. 17). Previous American and Soviet spacecraft lacked the ability to maneuver and dock in orbit; Gemini vehicles were able to effect translational motion and alter their orbital path, aided by the first onboard digital electronic computers, manufactured by IBM. (An even more robust system, designed at MIT, would guide Apollo astronauts to the Moon.) While the Soyuz eventually matched these achievements, extensive development problems and Korolev's death in 1966 delayed the craft's first piloted flight until 1967. This mission ended tragically when the vehicle was destroyed during landing, killing its pilot.

Fig. 17. ***This time-exposure photograph shows the configuration of Pad 19 up until the launch of Gemini X. Onboard the spacecraft are John W. Young and Michael Collins, who spent almost three days practicing docking with the Agena target vehicle and conducting several experiments. (NASA photograph.)***

The American space program suffered a similar setback that year, when an early direct version of its Apollo craft burst in flames during a launch pad test, killing the three astronauts who were to fly the craft into Earth orbit. The accident emphasized the inherent dangers of spaceflight, including the American practice, throughout the 1960s and 1970s, of pressurizing spacecraft with pure oxygen at reduced pressure, a technique that reduced stresses on the pressure vessel but introduced substantial fire risks. Following a redesign of the craft to limit the use of flammable materials within it, Apollo flew successfully the following year, in Earth orbit and, in a dramatic demonstration of the power and reliability of the Saturn V launch vehicle, the circumlunar Apollo 8 flight completed during Christmas 1968. Subsequent Apollo flights during 1969 verified the operating characteristics of Apollo's lunar lander, leading to Apollo 11's successful landing and return in July 1969.

While the Soviet Union continued its human lunar program into the early 1970s, it was ultimately unable to duplicate Apollo 11's feat and eventually abandoned the pursuit, turning instead to the launch of Salyut 1, the world's first space station, in 1971. Meanwhile, NASA entered a new phase of human spaceflight characterized by frequent, successful explorations in an environment of declining budgets. Following Apollo 11's flight, NASA launched six more Moon missions, five of them landing astronauts on the lunar surface (Fig. 18). While NASA had planned additional flights (including long-duration lunar stays), shrinking space appropriations forced their cancellation despite the fabrication of much of the necessary flight hardware. This surplus equipment facilitated the launching of America's first space station, the Skylab Orbital Workshop; a three-story pressurized enclosure manufactured from the tankage of the Saturn V's third stage. Skylab was visited by three Apollo crews during 1973 and 1974, conducting valuable research, particularly on solar astronomy. A subsequent joint rendezvous in Earth orbit of American Apollo and Soviet Soyuz craft in 1975 marked the end of Apollo and the last American crewed spaceflight until 1981, even though NASA did launch several robotic spacecraft during this period.

The success of the Apollo flights encouraged those who hoped that the United States would soon pursue an effort to establish a permanent lunar outpost and continue on to Mars, but support for such programs in Congress and from

Fig. 18. ***Astronaut John W. Young, commander of the Apollo 16 lunar landing mission, jumps up from the lunar surface as he salutes the U.S. Flag at the Descartes landing site during the first Apollo 16 extravehicular activity (EVA-1). Astronaut Charles M. Duke Jr., lunar module pilot, took this picture. The lunar module (LM) "Orion" is on the left. The lunar roving vehicle is parked beside the LM. The object behind Young in the shade of the LM is the far ultraviolet camera/spectrograph built by George Carruthers. Stone Mountain dominates the background in this lunar scene. (NASA photograph.)***

President Richard Nixon was not forthcoming. While the Soviet Union continued to develop its Soyuz spacecraft and Salyut space stations, the United States instead undertook the development of a reusable spaceplane boosted into orbit by a rocket, in a configuration reminiscent of 1950s designs. Larger than previous spacecraft and with a substantial internal cargo bay that could be used to ferry payloads to and from Earth orbit, the Space Transportation System (or Space Shuttle) would, NASA hoped, substantially lower the cost of placing payloads into low Earth orbit (LEO). The Shuttle's large crew cabin and more comfortable reentry profile also enabled nonpilots to fly in it, opening NASA's astronaut corps to women and ethnic minorities who had traditionally been underrepresented in military flight programs (and thus ineligible for previous selections). Competing design requirements ultimately produced a compromise craft with a variety of novel technologies. Among these was a reusable thermal protection system that replaced the ablative coating of Mercury, Gemini, and Apollo, with ceramic tiles that, while resistant to heat, proved physically vulnerable to damage.

Construction delays pushed the maiden flight of the American Space Shuttle until 1981, when the first Shuttle Orbiter Columbia launched with a partial crew on a brief Earth orbit flight intended to evaluate the vehicle's capabilities and undertake a synthetic aperture radar experiment (Fig. 19). Initial optimism about the Shuttle—and the prospects of private investment in its infrastructure—soon evaporated in a series of delays and cost overruns. Shortly after achieving operational capability, the Shuttle program, in January 1986, suffered the catastrophic loss of the Orbiter Challenger and its seven crew members, including a teacher chosen by NASA to inaugurate a presumed new era of routine spaceflight by nonprofessionals. Among the causalities of the tragedy was NASA's effort to promote the Shuttle as a commercial and military satellite carrier.

Upon the Shuttle's return to flight, the remaining shuttles (and an additional Orbiter constructed afterward) completed over 100 missions, launching the Hubble Space Telescope and a variety of other satellites and completing an ambitious international experimental program. Debate concerning the value of the Space Shuttle, already a controversial issue prior to the loss of Challenger,

Fig. 19. ***The same approach as used for the Saturn V launch process has been followed by the Space Shuttle program. Here the Space Shuttle rides on the crawler transporter en route to Launch Complex 39. Note the vehicles shown for the scale of this vehicle. (NASA photograph.)***

continued in the decades that followed. Higher-than-projected operations costs and lingering safety concerns saddled NASA with an expensive vehicle whose capabilities were limited to two-week flights into LEO. A 1987 plan by ESA to build the Hermes, a smaller Shuttle-like spacecraft, suffered repeated delays before its cancellation in 1992. Learning of the American program, the Soviet Union eventually developed the virtually identical Buran, which flew, unpiloted, on a single orbital test flight in 1988 before the program was canceled.

Two years earlier, the Soviets launched Mir, a space station greatly enlarged from the earlier Salyut design. Upon the collapse of the Soviet Union and the reorganization of the Russian space program, joint Russian–American flights resumed, culminating in the Shuttle visits to Mir in the early 1990s. Following the launch of the ISS in 1998, joint operations between American Space Shuttles and Russian Soyuz craft continued, with the ISS achieving continuous international human habitation in 2000. Throughout this period, both Russia and the United States explored replacement vehicles for existing Soyuz and Shuttle craft. In Russia, limited funding prevented the replacement of the Soyuz, which has been continuously upgraded during its nearly 45 years of service. Instead, Russia began offering seats aboard its craft to paying customers to offset the cost of its spaceflight operations, a program that orbited several space "tourists" but resulted in acrimony between Russia and its American partner, which has long resisted such efforts.

In the United States, several proposals to replace the Shuttle with a variety of spaceplanes ended in cost overruns and design failures, leaving NASA without a craft to replace the Shuttles as they approached the end of their design lifespan. The loss of a second Orbiter Columbia during reentry in 2003 emphasized the need to replace the Shuttle with more reliable craft, the design of which had yet to be determined at the time of the Shuttle program's final flight in July 2011. Proposed architectures have resurrected the capsule concept, now enlarged and with a variety of improved subsystems. It is with such a craft that NASA planners had hoped to undertake missions to return to the Moon and voyage to Mars. Unfortunately, funding for these efforts likely would permit only continued visitation to the ISS until its scheduled deactivation in 2020 or later.

In the absence of a clear programmatic effort in either Russia or the United States, a variety of other public and private entities have begun tentative space exploration efforts. In an effort to control costs and privatize spaceflight operations, the United States solicited the efforts of a variety of contractors to build piloted craft to service the ISS, while additional corporate entities are developing vehicles designed specifically to carry paying tourists on brief suborbital flights. In 2003, China became the third nation to launch humans into space, using its Shenzou, which are heavily influenced by earlier Soviet craft. To date, though, ambitious proposals to develop space stations and lunar vehicles appear to be progressing slowly.

In its 50-year history, human exploration of space has proven among the more breathtaking and controversial accomplishments of the modern technological state. Motivating continued investment in this technology is not a desire to accomplish specific exploration goals, but a conviction that space exploration plays a positive role in maintaining a nation's technological base, economic strength, defense capabilities, and national character. Though perennially criticized for its seeming extravagance, human spaceflight programs have resisted cancellation in both Russia and the United States, having become, over the past decades, something akin to a national treasure. And to a sizable community of spaceflight enthusiasts, futurists, and theoreticians, spaceflight represents humanity's greatest hope of achieving something akin to species immortality, regardless of Earth's future habitability.

III. COMMERCIAL SPACE ACTIVITIES (Roger D. Launius)

A core activity in space has long been economic in focus, and commercial applications represent an important aspect of space activities around the world. Space technologies, especially the complex human spaceflight component, demand a skilled and well-trained work force whose talents would be disseminated to the larger technological and economic base of the nation. Sometimes this commercial arrangement was indirect. The Apollo program, for example, served implicitly as an economic engine fueling the southern states' economic growth. In recent years, however, the economic rationale has become stronger and even more explicit as space applications, especially communications satellites, became increasingly central for sustaining economic competitiveness in space. The section explores these major areas of spaceflight since the flight of Sputnik in 1957 (Figs. 20 and 21).

A. Launch Vehicle Development/Access to Space (Deganit Paikowsky)

The ability to reach space and use it for different applications was made possible by the development of space delivery systems. Space access is, therefore, a key to all activities taking place there. Guaranteeing access to space is the first objective for countries engaged in launch capabilities development, either through indigenous efforts or international cooperation.

1) The Strategic Incentive—Between a Ballistic Missile and a Space Rocket: The first space launch vehicles (SLVs) were developed from ballistic missiles, which were developed mainly for military uses. In the United States, the Redstone, Atlas, and Titan rockets were modified to serve as SLVs and make possible the Mercury and Gemini

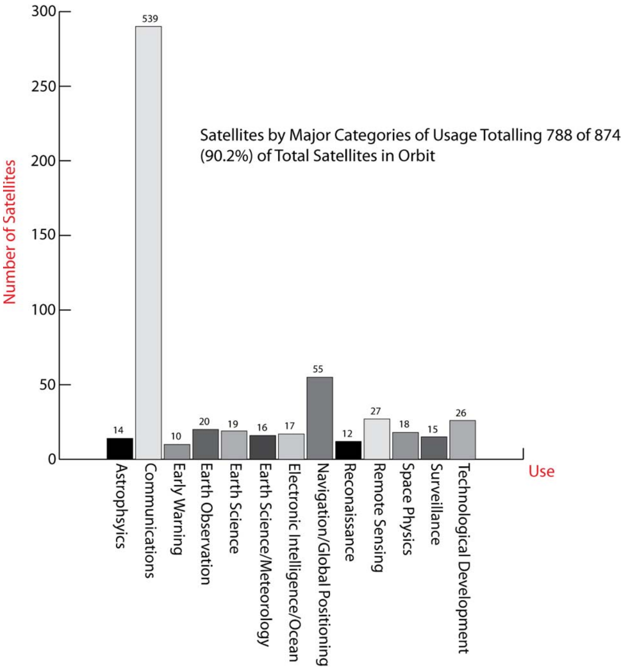

Fig. 20. ***Satellites in Earth orbit by major use as of 2009. (NASM illustration.)***

programs in the 1960s. Later, as the space programs of the United States and the Soviet Union progressed, launchers were developed independently of intercontinental ballistic missiles (ICBM); for example, the Saturn V used for the Apollo Moon missions and the Soviet N-1.

During the Cold War, the superpowers tightly controlled the use of SLVs, as well as the transfer of launching technology and know-how. Indeed, until 1965, the superpowers were the only ones capable of launching a satellite into space. During the Cold War years, eight states developed launch capabilities: France 1965, Japan 1970, China 1970, Britain 1971, India 1980, and Israel 1988. In the post-Cold War era, however, several additional states declared their ambition to develop launch vehicles, for example, South Korea and Brazil. Ukraine did not launch independently, but it manufactures the Zenit rockets launched by Sea-Launch, Inc., and therefore has an orbital launch capability. South Korea conducted a launch in August 2009, but failed to place the satellite in orbit. Iran performed an indigenous launch in February 2009. About 20 countries have at least a suborbital capability, which is the necessary step toward orbital rocketry. This effort had a significant effect on the space market throughout the Cold War and beyond. Currently, the number of nations capable of independently launching satellites into space is very low, considering the continuously growing number of nations that own satellites or use space applications.

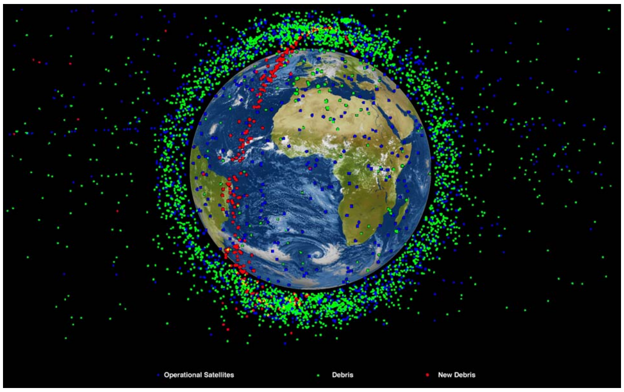

Fig. 21. ***Satellites in LEO are shown in this diagram. Operational satellites are shown with blue marks, while green makes indicate the location of disabled satellites and debris. Red marks show the volume of debris created by the destruction of the Fengyun-3A satellite in January 2007. (NASM illustration.)***

Fig. 22. ***From the earliest times of the Soviet Union's space program it decided to move launchers horizontally by rail from the assembly building to the launch complex. Presently at Baikonur Cosmodrome, the principal Russian spaceport, payloads to be fired into orbit are prepared for launch in a processing center a few kilometers from the launch site. The overall testing as well as fueling and pneumatic pressurization of the spacecraft take place there, and then the payloads are integrated with the rocket's upper stage. All of the rocket stages are sent by rail from the production plant, and mated for launch at this assembly point, before being loaded by cranes on a flat railroad transporter that will take it to the launch site, raise it vertically, and fire it into space. Here the Russian TM-31 Soyuz spacecraft approaches the launch complex on the horizontal rail car in preparation for its launch with a crew of three on October 31, 2000. (NASA photograph.)***

2) Space Launch Vehicle Technological Challenges and Characteristics: Most SLVs, like ICBMs, are expendable vehicles designed for one use only. They are characterized by the amount of mass they can carry, by the range they can reach; by the number of stages they employ; and by the launch platform: land, air, and sea (Fig. 22). Indeed, air launch requires a "mother ship" to take a vehicle to a speed and altitude where it is dropped while in flight. The rocket then fires its engines and propels itself upward. In the 1980s, the United States developed an air-launched miniature vehicle consisting of a two-stage missile deployed from an F-15 aircraft. This rocket was designed to reach LEO, target a satellite, and destroy it. In October 1985, it was tested but was not deployed. The only vehicle currently being air launched is the Pegasus flown from a Lockheed L-1011. It was developed in the late 1980s, flying for the first time on April 5, 1990. The debate over air launch intensified when discussions began on developing responsive space capabilities, which require affordable, rapid, and efficient access to space for lightweight, small satellites.

As of the 1990s, another method of accessing space is by launching from a floating platform. This method is being used by Sea Launch Company LLC, which was established in 1995 as a partnership between Boeing (United States), Aker ASA (Norway), RSC-Energia (Russia), and SDO Yuzhnoye (Ukraine). Its first test flight into orbit took place on March 27, 1999. Its first commercial payload was launched six months later. This capability has now built to a 92.6% success rate.

In the early days of the space race, SLVs were able to carry only a small amount of mass to a very short range, forcing the development and use of small miniaturized payloads providing very poor reliability rates. Sputnik1, launched in 1957, weighed only 84 kg. Gradually, technology improved. More than a decade later the American SaturnV launched the Apollo11 mission into lunar orbit carrying 43 811 kg. More than three decades later, the Shuttle missions to the ISS (about 400 km) weighed more than 110 000 kg each. As for reliability, it took the United States and the Soviet Union almost a decade to reach a 90% success rate. Today, reliability rates reach 95%–97%.

In the 1990s, after the Cold War ended and reliability rates improved, the technological challenges focused on reduction of cost to orbit and improving the reliability of launch schedules. These objectives remain acute today as organizations look to make space transportation similar to air transportation; achieving this goal is still far away.

3) Commercializing Space Transportation: First steps in commercializing space transportation began in the 1960s, but it took two decades before a global commercial launch industry had fully emerged as international organizations and private-sector firms made plans to launch a large number of communications satellites into geosynchronous orbit. In the 1980s the United States, Europe, the Soviet Union, and China took initial steps toward being competitors in the commercial launch market. These developments created conflicts among governments and between governments and the private sectors in the United States and Europe.

In the United States, both the Space Shuttle and expendable launch vehicles were available. In Europe, a quasi-private organization Arianespace was established to perform commercial launches using the European expendable launch vehicle Ariane, which was successfully launched into space for the first time in December 1979. A year later Arianespace conducted its first commercial launch, initiating a competition between the United States and Europe over commercial launch services.

After the Cold War ended space became a major business and the commercial launch industry saw vigorous growth. In the early 1990s, world government expenditures for launcher programs totaled \$2 billion. Two decades later in 2009 it totaled \$5 billion. Although launch to space holds only a small share of the global space market, it allows the existence of that market. Without the commercial ability to launch satellites into space, there would not have been a space market worth \$276 billion.

4) Outlook: Launch into space remains a technical challenge. It involves high costs, long lead times for scheduling flights, and rates of reliability far from optimal. The slow rate of technical innovation leading to improvements in launchers affects the overall global space market and prevents further advancement in space exploration and making flights into LEO a part of our daily life. The greatest challenge is, therefore, to progress toward a more reliable, safe, affordable, and advanced technology to access and travel through space.

B. Communications Satellites (David J. Whalen)

In fall 1945, Royal Air Force (RAF) electronics officer and member of the British Interplanetary Society Arthur C. Clarke wrote a short article in *Wireless World* that described the use of orbital satellites in 24-h orbits high above the world's land masses to distribute television programs (Fig. 23). Clarke is credited with conceptualizing geosynchronous satellite telecommunications. Even so, it was John R. Pierce of AT&T's Bell Telephone Laboratories who, in a 1954 speech and 1955 article, elaborated the utility of a communications "mirror" in space, a medium-orbit "repeater," and a 24-h-orbit "repeater." In comparing the communications capacity of a satellite, which he estimated at 1000 simultaneous telephone calls, and the communications capacity of the first trans-Atlantic telephone cable (TAT-1), which could carry 36 simultaneous telephone calls at a cost of \$30–50 million, Pierce estimated that a satellite would be worth a \$1 billion.

After the 1957 launch of Sputnik 1, many considered the benefits, profits, and prestige associated with satellite communications. Because of Congressional fears of "duplication," NASA confined itself to experiments with "mirrors" or "passive" communications satellites (Echo), while the U.S. DoD was responsible for "repeater" or "active" satellites which amplified the received signal at the satellite. In 1960, AT&T filed with the Federal Communications Commission (FCC) for permission to launch an experimental communications satellite with a

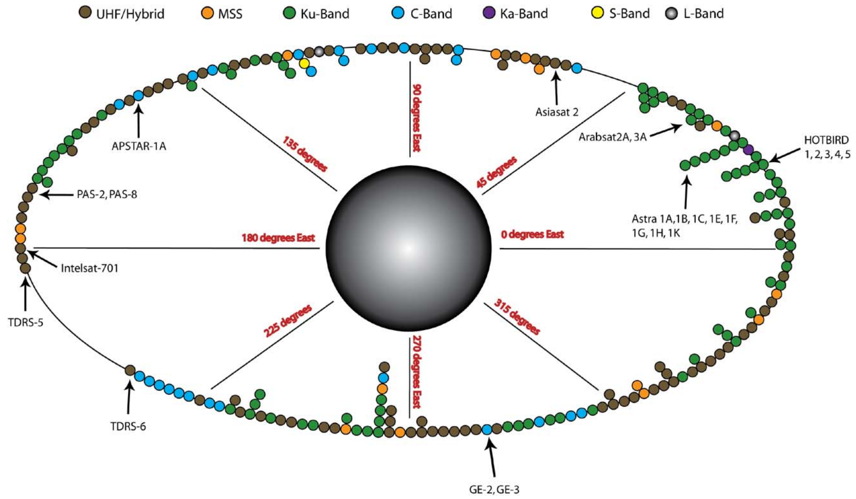

Fig. 23. ***This illustration shows the geostationary communications satellites by type of signal transmitted as of 2009. (NASM illustration.)***

view to implementing an operational system. The U.S. Government reacted with surprise—there was no policy in place to help execute the many decisions related to the AT&T proposal. By the middle of 1961, NASA had awarded a competitive contract to the Radio Corporation of America (RCA) to build active communication satellites (Relay) in an elliptical, medium-Earth orbit; AT&T was building its own medium-orbit satellite (Telstar), which NASA would launch on a cost-reimbursable basis; and NASA had awarded a sole-source contract to Hughes Aircraft Company to build a 24-h (37 000-km high) satellite (SYNCOM). The military program Advent was canceled a year later due to complexity of the spacecraft, delay in launcher availability, and cost overruns.

By 1964, two Telstars, two Relays, and two SYNCOMs had operated successfully in space. This timing was fortunate because the Communications Satellite Corporation (COMSAT), formed as a result of the Communications Satellite Act of 1962, was in the process of contracting for their first satellite. COMSAT's initial capitalization of $200 million was considered sufficient to build a system of dozens of medium-orbit satellites. For a variety of reasons, including costs, COMSAT ultimately chose to reject the joint AT&T/RCA offer of a medium-orbit satellite incorporating the best of Telstar and Relay. They chose the 24-h-orbit (geosynchronous) satellite offered by Hughes Aircraft Company for their first two systems and a geosynchronous satellite built by TRW for their third system. On April 6, 1965, COMSAT's first satellite Early Bird was launched from Cape Canaveral. Global satellite communications had begun (Fig. 24).

1) International Communications: Some glimpses of the Global Village had already been provided during experiments with Telstar, Relay, and SYNCOM. These had included televising parts of the 1964 Tokyo Olympics. Although COMSAT and the initial launch vehicles and satellites were American, other countries had been involved from the beginning. AT&T had initially negotiated with its European telephone cable partners to build Earth stations for Telstar

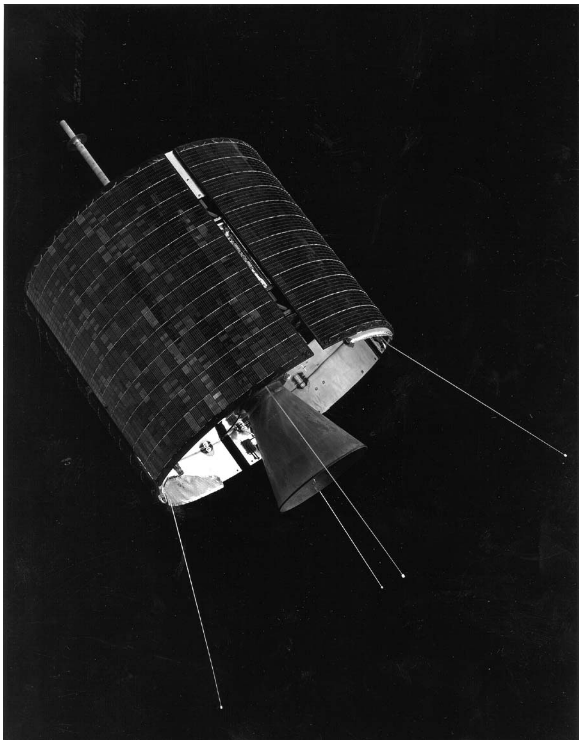

Fig. 24. ***Early Bird was the world's first commercial communications satellite. Built by the Communications Satellite Corporation (COMSAT) it was launched into geosynchronous orbit on April 6, 1965. With an orbit at 37 200 km above the equator, Early Bird provided line of sight communications between Europe and North America for telephone, television, telegraph, and facsimile transmissions. (NASA photograph.)***

experimentation. NASA had expanded these negotiations to include Relay and SYNCOM experimentation. By the time Early Bird was launched, communications Earth stations already existed in the United Kingdom, France, Germany, Italy, Brazil, and Japan. Further negotiations in 1963 and 1964 resulted in a new international organization, which would ultimately assume ownership of the satellites and responsibility for management of the global system. On August 20, 1964, agreements were signed which created the International Telecommunications Satellite Organization (Intelsat).

From a few hundred telephone circuits and a handful of members in 1965, Intelsat has grown to a present-day system with more members than the United Nations (UN) and the capability of providing hundreds of thousands of telephone circuits. Cost to carriers per circuit has gone from almost $100 000 to a few thousand dollars. Cost to consumers has gone down proportionally. If the effects of inflation are included, this was a tremendous decrease. Intelsat provides services to the entire globe, not just the industrialized nations.

2) U.S. Domestic Communications: In 1965, the American Broadcasting Company (ABC) proposed a domestic satellite system to distribute television signals. The proposal sank into temporary oblivion, but in 1972 Telesat Canada launched the first domestic communications satellite Anik to serve the vast Canadian continental area. RCA promptly leased circuits on the Canadian satellite until they could launch their own satellite. The first U.S. domestic communications satellite was Western Union's Westar I, launched on April 13, 1974. In December of the following year, RCA launched their RCA SATCOM F-1. In early 1976, AT&T and COMSAT launched the first of the COMSTAR series. These satellites were used for voice and data, but very quickly television became a major user. By the end of 1976 there were 120 transponders available over the United States, each capable of providing 1500 telephone channels or one TV channel. Very quickly the "movie channels" and "superstations" were available to most Americans. The dramatic growth in cable TV would not have been possible without an inexpensive method of distributing video.

The ensuing two decades have seen some changes. Western Union is no more. Hughes is now a satellite operator; its satellite manufacturing business is now part of Boeing. AT&T is still a satellite operator, but no longer in partnership with COMSAT. GTE, originally teaming with Hughes in the early 1960s to build and operate a global system, is now a major domestic satellite operator. Television still dominates domestic satellite communications, but data have grown tremendously with the advent of very small aperture terminals (VSATs). Small antennas, whether TV-receive only (TVRO) or VSAT, are a commonplace sight all over the country.

3) Technology: The first major geosynchronous satellite project was the U.S. DoD's Advent communications satellite. It was three-axis stabilized rather than spinning. It had an antenna that directed its radio energy at the Earth. It was rather sophisticated and heavy. At 220–450 kg it could only be launched by the Atlas-Centaur launch vehicle. Advent never flew, primarily because the Centaur stage was not fully reliable until 1968, but also because of problems with the satellite. When the program was canceled in 1962 it was seen as the death knell for geosynchronous satellites, three-axis stabilization, the Atlas-Centaur, and complex communications satellites generally. Geosynchronous satellites became a reality in 1963, and became the only choice in 1965. The other Advent characteristics also became commonplace in the years to follow.

JAXA and NTT developed the Communications Satellite (CS) series, called Sakura and launched between 1977 and 1988, to experiment with satellite control and to make propagation measurements in the 6/4- and 30/20-GHz bands in cooperation with the National Institute of Information and Communications Technology (NICT). The first Sakura pioneered the use of the 30/20-GHz bands for commercial satellite communications.

In the mid-1970s, several satellites were built using three-axis stabilization. The greater the mass and power, the greater the advantage of three-axis stabilization appears to be. Perhaps the surest indication of the success of this form of stabilization was the switch of Hughes, closely identified with spinning satellites, to this form of stabilization in the early 1990s. The latest products from the manufacturers of SYNCOM look quite similar to the discredited Advent design of the late 1950s.

Much of the technology for communications satellites existed in 1960, but would be improved with time. The basic communications component of the satellite was the traveling wave tube (TWT). These had been invented in the United Kingdom by Rudolf Kompfner, but they had been perfected at Bell Labs by Kompfner and J. R. Pierce. All three early satellites used TWTs built by a Bell Labs alumnus. These early tubes had power outputs as low as 1 W. Higher power (50–300 W) TWTs are available today for standard satellite services and for direct-broadcast applications. An even more important improvement was the use of high-gain antennas. Focusing the energy from a 1-W transmitter on the surface of the Earth is equivalent to having a 100-W transmitter radiating in all directions. Focusing this energy on the Eastern United States is like having a 1000-W transmitter radiating in all directions. The principal effect of this increase in actual and effective power is that Earth stations are no longer 30-m dish reflectors with cryogenically cooled maser amplifiers costing as much as $10 million (1960 dollars) to build. Antennas for normal satellite services are typically 5-m dish reflectors costing $30 000 (1990 dollars).

4) Mobile Services: In February 1976, COMSAT launched a new kind of satellite, Marisat, to provide mobile services to the U.S. Navy and other maritime customers. In the early 1980s, the Europeans launched the MARECS series to provide the same services. In 1979, the UN International Maritime Organization sponsored the establishment of the International Maritime Satellite Organization (Inmarsat) in a manner similar to Intelsat. Inmarsat initially leased the Marisat and MARECS satellite transponders, but in October 1990, it launched the first of its own satellites Inmarsat II F-1. The third generation, Inmarsat III, is now in service. Although Inmarsat was initially conceived as a method of providing telephone service and traffic-monitoring services on ships at sea, it has provided much more. The journalist with a satellite phone has been ubiquitous for some time, but the First Gulf War brought this technology into the public eye and it has expanded in use since then.

Inmarsat started with 2.4-m antennas on ships. Service soon evolved into the suitcase telephone and was followed by the briefcase telephone. The next step was the "satellite cell phone"—eventually recognized by the ITU as Global Mobile Personal Communications by Satellite (GMPCS). Most of these satellite cell phones systems were expected to be in low Earth orbit, but a few people thought that medium Earth orbit (MEO) would be better. Another choice was to place GMPCS systems in GEO, just like Inmarsat satellites, but with huge deployable antennas. Several of these systems were proposed, especially in India and China, and seemed ready to go, but only one actually flew: Thuraya, a UAE-based system. Thuraya's profitability may have been in large part due to U.S. military action in Iraq and Afghanistan—and the consequent need for enhanced communications.

5) LEO Systems: Cellular telephony has brought us a new technological system—the personal communications system (PCS). In the fully developed PCS, the individual would carry a telephone all the time. This telephone could be used for voice or data and would be usable anywhere. Several companies have committed themselves to providing a version of this system using satellites in LEO. These orbits are significantly lower than the Telstar/Relay orbits of the early 1960s. The early "low-orbit" satellites were in elliptical orbits that took them through the lower Van Allen radiation belt. The new systems are in orbits at about 830 km, below the belt.

The most ambitious of these LEO systems is Iridium, sponsored by Motorola. Iridium provides communications services to handheld telephones. It declared bankruptcy in 1999, was bought by a private equity group in 2000, and was eventually reorganized into Iridium Satellite LLC by a private consortium. Globalstar, another "big LEO" constellation, made money during the Gulf War and then declared bankruptcy in 2002, leaving it with large debts similar to those Iridium had before the 1999 bankruptcy. But Globalstar also survived as a new company.

6) Satellite Television: Arthur C. Clarke's 1945 vision involved three manned satellites located over the major land masses of the Earth providing direct-broadcast television. The inherent "broadcast" nature of satellite communications made direct-broadcast a recurrent theme, yet one not brought to fruition until the 1990s. The Direct Broadcast Satellite (DBS) race may have started with COMSAT's ill-fated Satellite Television Corporation (STC) in the late 1970s and early 1980s but it came to fruition with DirecTV-1, launched in December 1993, and has grown to tens of millions of subscribers and tens of billions of dollars in revenues. Its competitors include Dish Network. Dish Network's revenues are only about half of DirecTV's, but that still amounts to over $10 billion.

In addition to the "big LEOs," such as Iridium, there were several "little LEOs." These companies planned to offer more limited services, typically data and radio determination. Typical of these is ORBCOM which has become a leading provider of global satellite and cellular data communications purpose-built for asset tracking, management, and remote control.

7) Prospect and Retrospect: There were at one time six companies providing fixed satellite service to the United States: General Electric (GE) Americom, Alascom, AT&T, COMSAT, GTE, and Hughes Communications. They operated dozens of satellites with a net worth of many billion dollars. Only Americom and Alascom still exist; Americom is owned by a European company (SES) and Alascom is owned by the new AT&T (SBC). The Alascom satellites are owned and operated by SES Americom. The ground stations which communicate with these satellites are innumerable—their antennas measure from less than one meter in diameter to several meters—and probably exceed the value of the satellites. Since Canada began domestic satellite service in 1972, that country has been joined by the United States (1974), Indonesia (1976), Japan (1978), India (1982), Australia (1985), Brazil (1985), Mexico (1985), and many others. Each year from 10 to 20 communications satellites are launched valued at about $100 million each.

The launch vehicles placing these satellites in orbit have similar values. Both are multibillion dollar businesses. The ground station business is equally large. Finally, the communications services themselves are multibillion dollar businesses. John R. Pierce was right—it would be worth a billion dollars, but he underestimated; it is now worth over $200 billion.

8) Ka-band and the Internet: The Ka-band frequencies (30/20 GHz) were generally rejected because of the extremely large rain fade associated with them, but the prospect of thousands of megahertz available at Ka-band while C-band and Ku-band were saturated, was too much to ignore. There had been earlier experiments with Ka-band dating back to the 1970s, but it was NASA's ACTS (1993–2004) that proved that Ka-band was viable—at least experimentally. Many satellites, military and commercial, have been launched with a few Ka-band transponders—or even many Ka-band transponders. In heavy rainfall areas, the

Ka-band uplink can suffer 30 dB of rain fade and the downlink 20 dB of rain fade. This may not be fatal to packet transmissions, but makes Ka-band unsuitable for real-time TV. The jury is still out on Ka-band, but it has survived until now.

9) International: Satellite operators are found in almost every nation. The 1990s especially saw the rise of many Asian satellite operators. Actual hardware manufacture, however, has remained in the United States and Europe. The United States still manufactures the greatest number of commercial communications satellites, with European manufacturers close behind. After the export control imbroglio of 1998, many thought European "ITAR-Free" satellites would dominate the market; this has not happened. Japan, India, China, and Russia have also built communications satellites, but their commercial viability is still undetermined.

Launching communications satellites is a very different situation. The United States attempted to close down its expendable launch vehicle (ELV) lines in the late 1970s and launch everything on the shuttle. Then, in 1986, commercial payloads were banned from the shuttle after the Challenger disaster. The Ariane launch vehicle family took up the slack and has been near dominant in commercial launch services since 1986. The Chinese Long March started to compete in the commercial market, but seems to have been a casualty of the export control panic of 1998. Proton and Sea Launch have competed with Ariane in the last two decades. Unfortunately, the U.S. EELV program seems to have made the Delta IV and Atlas V too expensive for the commercial market. The United States is not a player in the market to launch commercial communications satellites.

C. Imaging, Reconnaissance, and Earth Remote Sensing (Eric Toldi)

When the United States and the Soviet Union committed satellites to the activities of the IGY of 1957–1958 their stated objective was to explore both the upper atmosphere and low Earth orbital environments. While both nations spoke of weather monitoring and international scientific collaboration they shared an interest in operating reconnaissance satellites over the territory of their opponent. This was particularly true in the United States, which desired information about closed-society Soviet activities (Fig. 25).

The first American imaging satellites were launched in 1960. Corona was a polar-orbiting satellite operated by the National Reconnaissance Organization (NRO) that used analog film rolls to photograph the globe. The capsule that contained exposed film reentered the atmosphere, deployed its parachute, and was recovered as it descended by an airplane. It was in this manner that a Corona return bucket containing film became the first object recovered from orbit. A related program Satellite and Missile Observation System (SAMOS) was a radio-relaying Air Force imaging satellite, as was the simpler Missile Defense Alarm System (MIDAS), deployed to detect Soviet missile launches. President Lyndon B. Johnson did not overestimate the importance of this technology in 1967 when he said that the United States probably spent between $35 and $40 billion on it, but "If nothing else had come of it except the knowledge we've gained from space photography, it would be worth 10 times what the whole program has cost."

While American efforts reflected the scheduling of the time thought appropriate to wage the Cold War, the Soviet reconnaissance satellite program was delayed because of the consistent success of the Experimental Design Bureau-1 (OKB-1) that created Sputnik. The first Soviet reconnaissance satellite Zenit utilized the same rocket and capsule design as the piloted Vostok spacecraft, which held priority in the Soviet space program through 1961. Zenit first successfully launched in 1962 and became a staple for the Soviet Union, operating for 30 years and producing the most spacecraft of any satellite program in history.

In 1960, additionally, the United States launched the first American weather satellite, named Television Infrared Observation Satellite (TIROS), as a joint effort between the Weather Bureau and NASA. In 1963, TIROS satellites began automated picture transfer, wherein unencrypted images were beamed from the platform to any receiving station, eventually allowing 120 nations access to weather imaging. In 1966–1967, the Soviets put up their own weather satellites, called *Cosmos Meteosats*, forming the experimental space meteorological system.

Fig. 25. ***Defense Support Program (DSP) satellites provide instantaneous detection of missile launches. (DoD illustration.)***

Starting in 1966, the United States began operating the second-generation Advanced Technology System (ATS) satellites in geosynchronous orbit. These experimental satellites pioneered many new technologies, including the first three-axis stabilization for constant global coverage and taking the first black and white and color pictures of Earth from that distance.

In 1972, as a portion of its post-Apollo restructuring, NASA launched Landsat, a multispectral Earth-observation satellite. Building upon the successes of the first decade of imaging satellites, Landsat included a three-axis stabilization system, was built by GE and operated by Goddard Space Flight Center, and uploaded its data to any recipient who built a receiving station. While the reconnaissance and weather monitoring satellites that came before had specific clients, Landsat was envisioned as a more broadly employed system. The satellites enabled the publication of the *Photo Atlas of the United States* in 1975, oversaw the results of the U.S.-exported/Soviet Union-imported wheat crop devastation in 1974 and 1975, as well as observed the U.S.'s Large Area Crop Inventory Experiment and Agriculture and Resources Inventory Surveys for NASA, the U.S. Department of Agriculture, and the new National Oceanic and Atmospheric Administration (NOAA).

In 1986, the French launched Satellite Pour l'Observation de la Terre, or Satellite for Earth Observation (SPOT), an Earth resources satellite. SPOT flew in a polar orbit, was three-axis stabilized, and although it captured only three spectral bands it offered stereoscopic imaging for 3-D Earth mapping. SPOT was also novel for being created as a commercial satellite, selling both its imaging data as well as conducting custom missions. In 1984, the United States attempted to make Landsat profitable by similarly privatizing it, and although this decision was overturned in 1992, that year also saw the passage of the Land Remote Sensing Policy Act, which authorized private imaging satellites.

After the *Challenger* accident of 1986, NASA conducted an audit of its activities and concluded that NASA should build on its earlier Earth science activities with the "Mission to Planet Earth" program. The program expanded a network of Earth Observation Satellites to monitor the sea, land, and air and to produce global system models. Although the core program was reduced and delayed many times, Aqua, Terra, and Aura launched in 1999, 2002, and 2004 allowed NASA to advance knowledge about planet Earth as a global climate system.

The 1990s and 2000s saw a number of international remote sensing missions, such as the U.S./French TOPography EXperiment/Poseidon (TOPEX/Poseidon) to measure sea-surface level and the U.S./Japanese Tropical Rainfall Measuring Mission (TRMM) to measure the global rain cycle, among many others. The increase of environmental systems modeling has been accompanied by a proliferation of commercial imaging satellites, providing accessible Earth-mapping capabilities.

D. Space-Based Navigation and Positioning Systems (Kerrie Dougherty)

One of the earliest satellite applications was the development of navigation and positioning systems (Fig. 26), initially intended to provide navigational data for military use, but today integrated into everyday life through an ever-burgeoning array of civilian devices and infrastructure systems that utilize the U.S.-developed Global Positioning System.

Although speculation about the possibilities of navigational satellites preceded the space age, in the latter 1950s, physicists at the Johns Hopkins University Applied Physics Laboratory (JHU/APL), after monitoring radio signals from

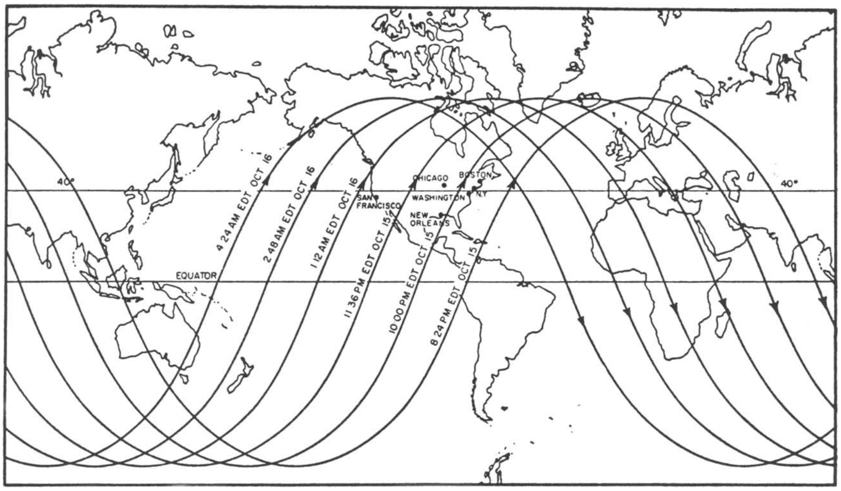

Fig. 26. *This plot showing the orbital track of the Sputnik 1 satellite was computed by scientists at suburban Washington's Naval Research Laboratory and released on October 15, 1957. It was the first instance of space tracking and navigation. (NRL photograph.)*

Sputnik, established that the Doppler shift of radio transmissions from a satellite in orbit could be used to determine position on the ground: if the path and timing of the satellite's orbit were precisely known, then the Doppler shifts of its signals could establish the location of a terrestrial receiving station.

This Doppler positioning technique became the basis of the first navigational satellite Transit, initially created to provide location data for U.S. ballistic missile submarines in order to improve targeting accuracy. The first successful Transit satellite (Transit 1B) was launched in 1960, with the system becoming operational in 1964. The Transit system employed a constellation of six satellites (three operational and three on orbit spares) in polar orbits at an altitude of approximately 1100 km, enabling vessels to determine their positions to an error radius of about 80 m. Civilian access to Transit became available in 1967 and it was widely adopted by commercial shipping in the 1970s: it was also extensively used for surveying applications. With the orbiting of the NAVSTAR Global Positioning System, the Transit system was phased out in 1996.

Like the United States, the Soviet Union recognized the value of a satellite navigation system for its ballistic missile submarines and developed the Tsyklon/Parus system, which had a similar technology and comparable accuracy to Transit. The first experimental Tsyklon satellites were launched in 1967, with the operational Parus system coming into service in 1976. Parus satellites occupied six 83° inclination orbits at an altitude of 1000 km. A simplified civilian version of this system, known as Tsykada, using four satellites, was initiated in 1979 for use by Soviet merchant vessels and the Soviet Navy. The Parus and Tsykada systems remain in use today.

Alongside Transit's Doppler-based method of determining position, another technology was investigated in the 1960s to meet the navigation and positioning needs of the U.S. Navy and Air Force. This new approach was based upon establishing position using "trilateration," in which the precision timing of signals from three (or more) satellites is used to determine an accurate position fix. After the Naval Research Laboratory's Time and Navigation (TIMATION) satellites, launched in 1967 and 1969, demonstrated the feasibility of a trilateration-based system using high-precision clocks, a new satellite navigation project emerged in 1973 under U.S. Air Force management—the Navigation Signal Timing and Ranging Global Positioning System (NAVSTAR GPS) program, which is today commonly known simply as GPS (Fig. 27).

GPS provides a very precise positioning, navigation, and timing signal which can be used to pinpoint a location within several meters or less, depending upon how many satellites are available when taking a fix. A GPS receiver works by measuring the relative time delay of signals from at least four GPS satellites, each of which carries onboard atomic clocks. Of course, the number and type of clocks has varied with successive satellite generations. Each Block I NAVSTAR GPS satellite contained one cesium and two rubidium atomic clocks. Block II/IIA satellites carried four atomic clocks, two cesium and two rubidium, while Block IIR satellites each carry three rubidium atomic clocks. These precision timekeepers are accurate to within 1 s per 300 000 years. The relative times are mathematically transformed into three spatial coordinates and one time coordinate (accurate to within about 50 ns). The concept validation "Block I" NAVSTAR satellites, launched between 1978 and 1985, operated in circular 20 200-km orbits, with a 12-h period. They were positioned in six orbital planes at an inclination angle of 63°. The operational GPS satellites, with successive generations to date designated Block II, Block IIA, Block IIR, Block IIR-M, and Block IIF, operate in the same six orbital planes, with four satellites per plane, but at an inclination of 55°. They commenced launching in February 1989.

Originally restricted to military use, a "degraded" GPS signal was made available for civilian use in 1983 under a technique known as selective availability, which introduced a deliberate error into the civilian signal to reduce its accuracy. The loss of flight KAL 007, shot down by the Soviet Air Force after the aircraft strayed off course into Soviet airspace, prompted U.S. President Reagan to announce in September 1983 that the GPS system would be made freely available for civilian use, to avert similar navigational errors in future. To improve the accuracy of the civilian signal, a wide variety of "differential" GPS methods were developed: so successful were they in overcoming the limitations of selective availability that the restrictions were removed in 2000, making the higher precision signal available to all users. Once this occurred, the civilian use of GPS exploded, with a huge range of applications, utilizing both the positioning and precision time signal capabilities of the system, becoming

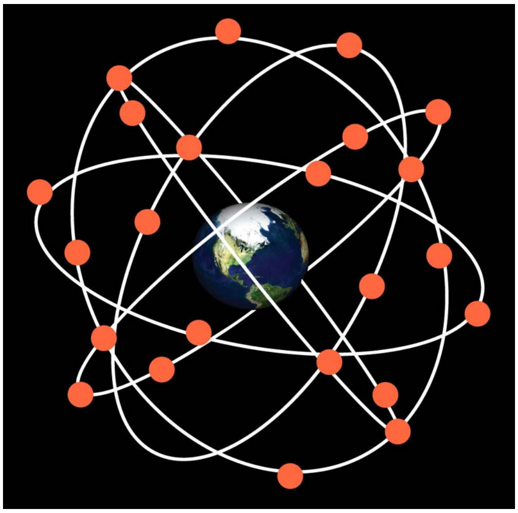

Fig. 27. ***The GPS requires at least 24 satellites to be fully operational and provide global coverage. Satellites are placed in four orbital planes. The GPS satellite orbits at half the distance to geosynchronous orbit, thereby taking 12 h to complete each orbit. (NASM illustration.)***

embedded in civil and commercial infrastructure and the social fabric of everyday life.

The Soviet Union also developed a trilateration-based navigation system as a complement to its Tsyklon/Parus/Tsykada satellites. Known as the Global Navigation Satellite System (GLONASS; the acronym is the same in Russian and English), this system was designed to employ 24 satellites, like GPS, but in three orbital planes at an inclination of 64.8°, with an orbital altitude of 19 100 km. GLONASS was declared fully operational in 1995, although financial difficulties in Russia during the 1990s led to the system falling into disrepair, as nonfunctioning satellites were not replaced due to lack of funds. The system has, however, been refurbished and revitalized since 2003, with the Russian equivalent of selective availability removed in 2007.

The incorporation of GPS into so many areas of civil, commercial, and military activity, coupled with concerns about the consequences should the United States reintroduce selective availability (the U.S. Government announced in September 2007 that the future Block III GPS satellites will not have the capability for selective access installed, or otherwise restrict access to the GPS signal) has encouraged other nations to develop their own satellite-based navigation systems. The European Union's Galileo positioning system will consist of 30 spacecraft in three orbital planes at 56° inclination, operating at an altitude of 23 222 km. Testbed satellites have already been launched and the system is expected to commence operation in 2014.

China's Beidou 1 national system began in 2000 and uses four satellites in geostationary orbit. Its global Compass (Beidou 2) system, utilizing 35 satellites in geostationary, medium Earth orbit, and inclined geosynchronous orbit will become operational in 2012 providing an Asia-Pacific regional service, with full global service to follow. India is similarly developing its Indian Regional Navigational Satellite System (IRNSS), which is intended to provide an absolute position accuracy of less than 20 m throughout India and within a region extending about 1500 km around it. The proposed system would initially consist of a constellation of seven satellites in geostationary and inclined geosynchronous orbits.

IV. OUTER SPACE AND NATIONAL SECURITY (Peter L. Hays)

The United States has developed space capabilities to enhance national security from before *Sputnik* to the present. Desires for better intelligence on the strategic capabilities and intentions of the closed Soviet state became a primary security concern for the United States at the onset of the Cold War. Several ominous developments in the late 1940s and early 1950s underscored this need including inaccurate predictions on when the Soviets would first develop atomic weapons and have operational thermonuclear weapons, uncertainties about a possible bomber gap, the failure of President Dwight Eisenhower's freedom of overflight in space proposal of July 1955, and many issues related to the progress and strategic impact of the Soviet intercontinental ballistic missile ICBM program. Even in the earliest days of the Cold War some visionaries believed that space might provide an ideal vantage point for spying on the Soviets. The first report from the RAND Corporation, "Preliminary Design of an Experimental World-Circling Spaceship," completed in April 1946, not only explained space physics and spaceship technical designs but also introduced almost every one of the major military space missions that would be developed in the coming decades including communications, attack assessment, weather reconnaissance, and strategic reconnaissance.

RAND also became the first organization to analyze comprehensively the political implications of the opening of the space age in an October 1950 report that highlighted the likely psychological impression the first satellite would leave on the public and raised the critical political issues of "overflight" and "freedom of space"—asking how the Soviets would respond to new issues in international law such as satellites flying over and photographing their territory. The report suggested that one way to test the issue of freedom of space would be first to launch an experimental U.S. satellite in an equatorial orbit that would not cross Soviet territory before attempting satellite reconnaissance over the Soviet Union.

By the mid-1950s, development of aircraft and photoreconnaissance satellites with the potential to help open the closed Soviet state became the top U.S. space-policy goal. To support this highest priority objective, U.S. space policy concurrently sought to build and protect a legal regime designed to legitimize the operation of spy satellites. President Eisenhower's approach toward space and strategic issues was strongly influenced by the top secret Technological Capabilities Panel (TCP) he commissioned in March 1954. The TCP completed a secret two-volume report and briefed the National Security Council (NSC) in February 1955. The report strongly recommended rapid development of U.S. technical intelligence-gathering capabilities and supporting policies for overflight, urging construction and launch of a small scientific Earth satellite that would operate above the sovereign airspace of states. The TCP process and report were critical drivers behind development of America's first high-tech intelligence collection platforms: the Lockheed U-2 aircraft and the weapons system (WS)-117L reconnaissance satellite program that eventually led to successful operation of the Corona system in August 1960. Prompted by the TCP and other developments, the NSC undertook a delicate and hidden task, development of America's first national space policy: NSC 5520, "Draft Statement of Policy on U.S. Scientific Satellite Program," approved by President Eisenhower on May 27, 1955. NSC 5520 was a secret document that indicated the United States should call attention to its scientific satellite program for the IGY but secretly place more emphasis on preserving freedom of action in space, using the benign IGY program as a "stalking horse" to establish the precedent of space overflight and legitimize eventual operation of military reconnaissance satellites.

Beyond reconnaissance satellites, by the early 1960s, the military of both the United States and the Soviet Union was working hard to develop a comprehensive range of space capabilities. Most of those early missions were originally designed around direct support for strategic nuclear operations, such as the infrared sensors on the American Midas and then Defense Support Program satellites that provided early warning of ICBM launches. Both the U.S. Army and the Air Force also deployed a small number of nuclear tipped antisatellite (ASAT) missiles in the Pacific but these systems had limited capabilities, were unable to discriminate between friendly and enemy satellites due to their nuclear kill mechanism, and were abandoned by the 1970s. In addition, the U.S. Air Force was eager to develop a full range of military space capabilities including military space stations and spaceplanes supported by military astronauts. These grand ambitions were repeatedly thwarted by civilian leadership, due primarily to the U.S. Air Force's difficulty in articulating a strong rationale for these expensive programs. By the end of the 1960s, following cancellation of the X-20 Dyna-Soar spaceplane and the Manned Orbiting Laboratory, the military was largely resigned to viewing space as a sanctuary and concentrated primarily on improving the ability of space systems to support terrestrial operations rather than focusing on warfare in space (Fig. 28).

Fig. 28. *The United States also pursued the X-20 Dyna-Soar in the 1960s, a military spaceplane to be launched atop a newly developed launcher. The U.S. Air Force believed that the X-20 would provide long-range bombardment and reconnaissance capability by flying at the edge of space and skipping off the Earth's atmosphere to reach targets anywhere in the world. Begun on December 11, 1961, this spaceplane was always troubled by the absence of a clearly defined military mission. Accordingly, in 1963, Defense Secretary Robert S. McNamara canceled the program. (DoD illustration.)*

By the end of the Cold War, military space capabilities had matured significantly and were used in novel ways that transformed terrestrial warfare. Space-enabled warfare first emerged in a comprehensive and very public way in the First Gulf War in 1991. In this instance, space capabilities that had been designed to support strategic and nuclear operations were reconfigured to support a range of tactical operations, including battle damage assessment and long-range precision strike. These changes accelerated and became a dominant form of warfare during the ensuing years, with specific operations in Kosovo, Afghanistan, and Iraq. Today, the U.S. military engages all time-critical or high-value targets with space-enabled long-range precision strike weapons, and space capabilities enable almost all routine military operations at a fundamental level.

The UN addressed in 1967 the issue of military activity in space with the "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies." Enduring issues that remain and may become more important as we approach the first century of military space operations include the best political and diplomatic approaches to improving the resiliency of space capabilities and questions concerning the adequacy of the current space governance regime in promoting responsible behavior as space becomes an increasingly congested, contested, and competitive environment.

V. WHAT MIGHT THE FUTURE HOLD? (Jennifer Levasseur)

Looking forward from today, attempting to conjure a vision of future space activities, seems strangely familiar when looking back at the history of space exploration. Many of the same questions and problems still exist but with just a slightly better understanding of the universe in which we live. Our prospective future includes the same goals it did 50 years ago—interplanetary human exploration, creating robotic assistants, astronomical research, and observing the Earth—all ideas significantly tempered by the realities of life on Earth, and declining prospects for major government expenditures for space-related projects.

What people imagined for the future in 1950 included much of what we know today: a human-tended space station, communications and reconnaissance satellites, orbiting telescopes, and robotic explorers. But moving forward, scientists, engineers, politicians, and the public will continue to revisit the questions from our first round of spaceflight experiences. How do we get into space? What do we do when we get there? How does humankind benefit from going to space? These questions and others about pragmatic issues like budgets, priorities, and resources mirror those of the past, but seem likely to have drastically different answers as factors of population, environment, and economics shift over time. But examining ourselves from space, a process begun with high altitude images of the 1940s, appears likely to continue as our primary objective in space—increasing our knowledge of the Earth's resources, its weather, global communications, and space-based intelligence gathering.

Space science thrives today, perhaps more than any other form of space application, thanks to its foothold in the public imagination through the visual evidence it provides. Multinational successes continue to drive unlocking the mysteries of near and distant cosmic destinations on missions like the Mars Exploration Rovers Cassini and the continued travels of NASA's Voyager probes. The tremendous success of the Hubble Space Telescope, Cosmic Background Explorer (COBE) and ESA's Herschel Telescope supplied even more unknowns about our universe and, perhaps, our first reasons to believe in life beyond this "pale blue dot." Despite some notable failures, future prospects for a robust international effort to understand our universe through scientific observation seem certain.

From the heights of lunar exploration to the depths of the end of the Space Shuttle program, human spaceflight continues to travel along a roller-coaster-like trajectory in the hearts and minds of a population typically more concerned with terrestrial issues. If the first half of this period is marked by developing launch vehicles for space access, the start of the second half appears to be on a similar path. The quest for reliable, low-cost means to access space continues in the United States, while European, Russian, Chinese, and other programs have developed and maintained consistently successful launchers.

Moving forward, new commercial enterprises will continue to enter the space arena, offering their vehicles for launches, but none have as yet offered innovative propulsion methods. Humans appear restricted to Earth orbit for the foreseeable future in a world of solid and liquid chemical propellants. And while six people orbit the planet onboard the ISS today, prospects for going to the Moon, Mars, or an asteroid become more dim as the financial and biological risks rise exponentially (Fig. 29). From all appearances, our future looks quite a bit like our present: an endless quest to learn more about the cosmos and ourselves while struggling to further the technologies necessary to move beyond Earth on a permanent basis. There will be both accomplishments and failures that have been anticipated, accomplishments and failures that were not envisioned, and most importantly surprises that were not anticipated.

Fig. 29. ***This fanciful depiction from 1995 of a major industrial park on the lunar surface captures well the excitement of what might take place once humans make the Moon a second home. (NASA illustration.)***

Two visions of the future of spaceflight are offered below. The first is from Ralph L. McNutt Jr. of APL, and the second is from Brent Sherwood of JPL.

A. Looking Forward (Ralph L. McNutt Jr.)

Looking forward to what might come next in space has been a cottage industry since well before the Space Age itself. Despite this popular interest, and the flights of fancy it sometimes entails, the constraints of reality must inform predictions of what are likely—as compared with possible—futures. In any case, such constraints lead to four broad requirements if we are to move forward in space:

1) national policy/science: the case to go;
2) technology: the means to go;
3) strategy: the agreement to go;
4) programmatics: the funds to go.

In the United States, national policy for space has been articulated in one guise or another by Presidential administrations since the 1950s. Most recently, both George W. Bush and Barak Obama administrations stated a broad vision that included possible human lunar exploration as well as missions beyond the Moon, with Mars as a potential target for human exploration before the middle part of the 21st century. At the same time, space science planning studies have made well-articulated cases for scientific goals and missions throughout the Solar System. Hence, point 1 ("national policy/science: the case to go") has been fulfilled. Pointing to explicit policy documents in other countries is not as easy a task, but the budgets and initiatives of other spacefaring nations speak for themselves. Indeed, the recent *Global Exploration Roadmap* (http://www.nasa.gov/pdf/591067main_GER_2011_small.pdf) subscribed to and endorsed by 12 national and international space agencies echo similar goals and aspirations. Similar goals have also been articulated by the nongovernmental International Academy of Astronautics through the "Heads of Space Agencies Summit" of November 2010 (http://iaaweb.org/content/view/393/591/).

At the current epoch, however, the future is cloudy as the other points remain to be worked. For every space agency, the path of technology development (including the necessary funding) is highly contingent upon the details of the strategy to be pursued. In the United States, the programmatics of funding—over multiple U.S. Congressional election cycles—remains in question and plays against aggressive exploration; reaching engineering closure on technical implementation requires programmatic consensus first.

While many analogies have been drawn between space exploration and the "age of exploration," one significant difference remains: the European explorers of the 15th, 16th, and 17th centuries not only made the case for making a profit to their sponsors, but also the profits—and large ones—did materialize after none too many years. Commerce and the profits that drive it have found their niches in Earth orbit in the form of communications around the globe, weather tracking and forecasting, and resource location and tracking. Such Earth orbital resources will likely continue to expand, especially in support of current third-world nations that lack land-based infrastructure, but what of other orbital resources?

Beginning in the late 1960s, studies of Solar Power Satellites (SPS) to convert sunlight to microwaves and beam energy to the surface of Earth have provided a technical basis for going forward with pilot projects, but they also suggest large infrastructure costs that, to date, have precluded widespread development and use (Fig. 30). In particular, space transportation costs and solar array manufacturing costs are significant issues for such future development. At about the same time, Gerard O'Neill of Princeton University led a full-up study assessing the possibilities of colonies in space that might support these SPS activities. While this marriage of colonization and SPS promised to make a colony self-sustaining, costs were again a driving issue (Fig. 31). The scenario developed during these reviews predicted a space colony would yield a positive cash flow only after 27 years and $44 billion of sunk costs in 1975 dollars. Such large-scale orbital space projects continue to be stymied for lack of a sound business case.

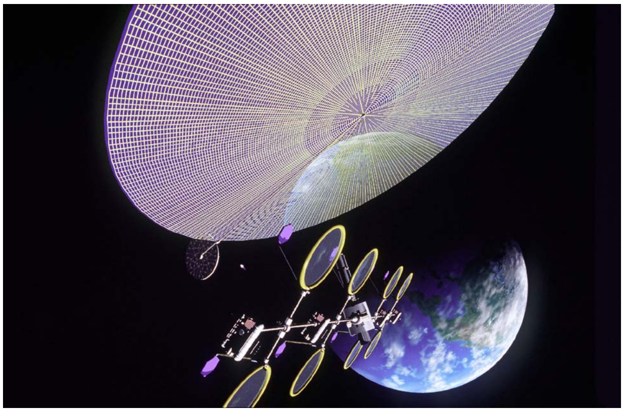

Fig. 30. ***Artist's conception of solar power satellites, after 2035. Advocates of one persistent vision foresee the use of solar power to replace fossil fuels. A Solar Disk could direct high-energy beams to power stations on Earth. Solar power is not likely to be economically competitive relative to ground-based 21st century alternatives like hydrogen-powered fuel cells. (NASA illustration.)***

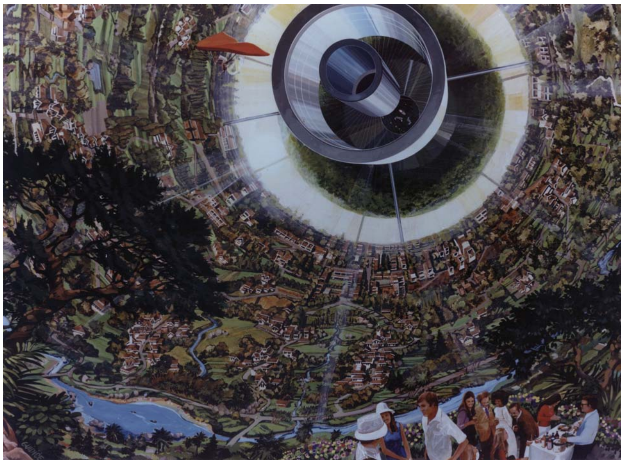

Fig. 31. ***Artist's conception of a space colony. During the 1970s, physicist Gerard O'Neill proposed the establishment of very large colonies in the emptiness of space as a means of relieving population pressure on Earth. The concept, which attracted many followers, is not a feasible solution in the near term. (NASA illustration.)***

Fifty-year projections are easy to make but hard to implement. From Dandridge Cole's work of 1965 (projecting to 2015) through the "Paine Report" of 1985 (projecting to 2035) and the "Stafford Report" of 1991 (projecting only to a targeted human landing on Mars before 2020), lack of developed technologies and, ultimately, money have dashed all hopes of expansive space operations. The past can inform the future, but sometimes the results are not what one might prefer. The reality is that there is no item in sight for making the business case for deep-space (beyond Earth orbit) missions—robotic or human—as a profit-making enterprise. So, the Solar System, from cis-lunar space to the fringe of the Kuiper-Belt and beyond will remain a government—or governments—financed activity through 2060 at the least.

Is there any other example of such an enterprise, born of national security concerns and ending up as an international venture to the advantage and betterment of all parties while increasing human knowledge? And has a 50-year track record, to boot? The answer is a resounding "yes," and the location is Antarctica. While the Antarctic continent was "discovered" (by Europeans anyway) in the 18th century, it emerged as an item of international

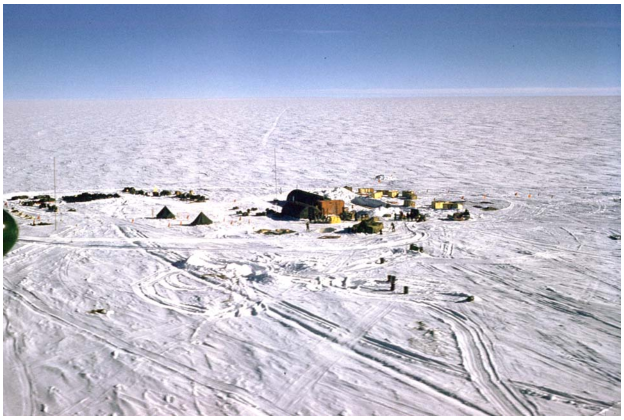

Fig. 32. ***Aerial view of the first permanent station built at the South Pole, taken on December 4, 1956. The U.S. Navy built seven stations, including one at the South Pole, in support of the IGY. (Photograph by Dick Prescott. Courtesy of the National Science Foundation, Washington, DC.)***

competition in the latter 19th century. To quell that competition, the IGY of the austral summer of 1957–1958 led to a defusing of national rivalries culminating in the Antarctic Treaty and continuous habitation on that continent, including at the South Pole, for over 50 years (Fig. 32). As an international territory governed by that treaty, Antarctica has yielded scientific information on astrophysics, climate, geology, and meteorites in an environment that has led to an overall increase of human knowledge as well as international cooperation.

During the next 50 years, through approximately 2060, use of near-Earth space for all sorts of commercial activities, including communications, data transfer, weather prediction, Earth resources monitoring, and national security monitoring, will most assuredly continue. Whether suborbital—and even orbital—commercial space travel, i.e., not government supported, will emerge is an experiment in the making. The business case for "space tourism" is yet to show a profit, and travel to space for running experiments is likely to remain government funded, if not government run, as is access to the ISS.

Human spaceflight has several potential flexible paths forward: a return to the Moon, visits to near-Earth asteroids (NEAs), or a direct, first flight to Mars. The technical difficulties of these paths are very different. The Moon is roughly three days from Earth on a minimum-energy trajectory. While a variety of technical problems could lead to mission failure, the technical capabilities required for a lunar mission are minimal. Round-trip missions to a tiny number of identified near-Earth asteroids could perhaps also be carried out, but the challenges for propulsion and life support remain significant.

Human missions to Mars, the *raison d'être* for many supporters of human exploration, lie within reach over the next 60 years, but just barely. Studied for over 60 years, the problems and issues are well known. Minimum-energy, round-trip, "conjunction-class" missions would require about 10 km/s of total speed change and about a 1000-day trip, with about half of that on the surface of Mars (or at least in the Mars system). Relatively short "opposition-class" missions would require about half the trip time and have only ~30-day stays on the surface but at the price of significantly more propulsive capability. Longer times in transit mean a longer exposure time to galactic cosmic rays (GCRs) and solar energetic particles. The question of the effects of radiation is complex with conjunction-class missions at the least increasing the lifetime cancer risk of the astronauts. The true extent of radiation effects on such long trips remains uncertain, largely due to the high-energy, high-atomic number (HZE) and high-energy proton GCRs, both of which are largely shielded from the surface of the Earth by the combination of the Earth's magnetic field and atmosphere. Long-term deleterious effects of microgravity are known but countermeasures are challenging. These issues of human health must be weighed against trip time, and therefore, technical aspects of propulsion systems.

While "analysis battles" will continue to be waged on human spaceflight, robotic missions have enjoyed significant headway in our exploration of the Solar System. As the measurements advance and become more difficult to make, the associated prices of the missions do continue to rise. Again, deep-space missions will only be on the agendas of governments, as they involve long-term, fundamental research with unknown payback times and effectiveness.

The difficulties are illustrated by the troubles that the Hubble Space Telescope had with its initial startup as well as by the current, unplanned development costs being accrued by the James Webb Space Telescope (JWST). If the former is any guide, JWST will be successful and likely will enjoy a 20-year or so life span (reaching to the late 2030s). With those technologies in hand, a possible resurgence in interest in actually building what was once called the Terrestrial Planet Finder (TPF) may emerge. Building upon current work by the Kepler mission and others, by the early 2020s, there should be a good knowledge of what to target with a TPF, and what it would cost to build. Experience with JWST at the L2 Lagrange point may also provide an entrée for establishing more observatories there as well as a human transfer capability (about a 30-day trip each way) for the servicing and extension of life for satellites posted there.

Robotic probes have continued to explore new worlds. The recently released Planetary Decadal Survey provides a national plan for building upon this exploration and its associated scientific discoveries in the next decade. While continuing smaller and medium missions, this survey urges the nation to begin a program leading to return of pristine rock and soil samples from Mars as well as to search Jupiter's moon Europa for signs of a habitable zone, driven at least partially by the radiation field of Jovian space near that moon. With adequate funding, the sample

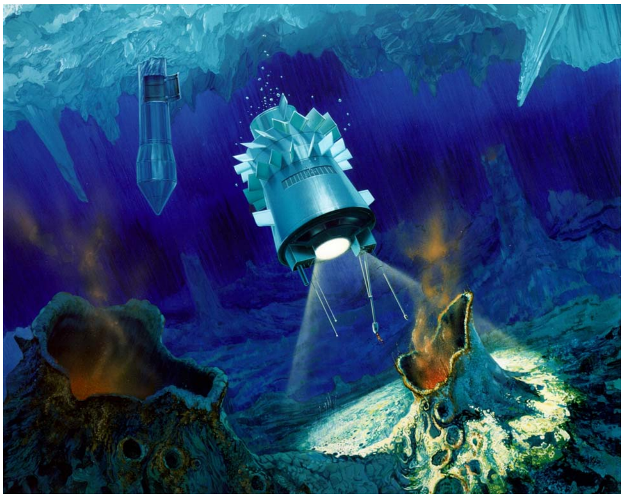

Fig. 33. ***Artist's depiction of the discovery of life on Europa, about 2025. A cryobot has melted its way through the icy crust of Europa, one of Jupiter's largest moons. Emerging below the ice, it releases a hydrobot, which searches for geothermal vents that may harbor life. (NASA illustration P-48326, 1997.)***

return could be conducted by the 2030s, while detailed investigations of Europa could commence within a decade of the late 2020s (Fig. 33). Concentrated looks at other possible prebiologic environments at Titan and Enceladus in the Saturn system are other possibilities, with the missions only limited by funds available. Given the pace of these "flagship" missions, the 2040s and 2050s could see the results from long-lived Venus landers as well as orbiters of Uranus and Neptune, with concentration in the latter's system on its enigmatic moon Triton. As mission difficulty and hence mission costs have escalated, national agencies have looked at teaming arrangements. A U.S. document, the Decadal Survey, looked to teaming with ESA for both future Mars and Jupiter-system endeavors. Japan and India are currently looking forward to returns to asteroids and the Moon. The Bepi-Colombo mission to Mercury, to be launched in 2014, is a joint ESA-JAXA venture. Mars continues to be a significant target for exploration outside the United States, but the difficulties associated with even robotic exploration of such a "close" target were recently reemphasized by the failure of the Russian Phobos-Grunt mission. As long as such missions are relatively infrequent, risks of failure will remain.

In the "border region" between Earth applications satellites and deep-space planetary probes there would be more missions to understand the Sun and its influence upon the Earth and the rest of the Solar System in both fundamental and applied aspects. So-called "space weather" has become more and more of a subject of relevance for our increasingly technological society, from impact upon wireless communications to effects on long-haul power transmission lines to knowledge of radiation-background effects on crews of polar-route aircraft. In the 2020s, data from the proposed U.S. Solar Probe Plus and the ESA Solar Orbiter are projected to give us unprecedented insight into the physical mechanisms by which the Sun affects our space and technological environment. Perhaps as early as the mid-2020s an International Interstellar Probe could be launched to take over the quest for knowledge begun by the Voyager 1 and 2 spacecraft, continuing humanity's reach into the plasma, particles, and fields occupying the space beyond the Sun's reach, between the stars.

Sine qua non for these further investigations of our own Solar System would be reliable isotopic power supplies (including a reliable source of the artificial isotope Pu-238), larger—and affordable—launch vehicles, and a renewed and upgraded Deep Space Network, likely expanded to having international connections to shared facilities.

A difficult issue will be deciding what to do about returning samples from planets to Earth for further study. There has been, and continues to be, debate about the pros and cons of studying materials *in situ* versus going to the trouble and expense of returning them to Earth. Ultimately, the scientific infrastructure and equipment needed for the most detailed investigations is too massive or sensitive to transport off planet, and especially not on an autonomous robotic mission. The debate over returning sample from Mars has made this clear, with at least some of the thinking guided by the scientific advances from lunar samples brought to Earth by the Apollo astronauts. The most significant reason for returning samples is to establish a reliable chronology of the forces and events that shaped the Solar System and led to the habitability of Earth. Robotic sample returns from either Venus or Mercury would be difficult; indeed it is not clear which would be the more difficult environment from which to retrieve a sample, but those tasks offer enticing possibilities for missions in the latter half of the 21st century.

Fifty years from now we may have businesses in near-Earth space, but the cis-lunar reaches and beyond will likely remain within international and quasi-government control. Our knowledge of our surroundings can be fueled by a healthy robotic program with eyes looking back in time to dark energy and outward to possible other terrestrial exoplanets. Our knowledge of how the Sun acts and reacts with the Earth through space will be refined and made predictive with physics-based models and space weather forecasts a commonplace. Exploration of the Solar System will continue—with robots always taking the first, and to some extreme environments the only, steps. We can choose to go to Mars, but we will need new and reliable propulsion to do so along with better studies of our own physiology and limitations in extreme environments. The Moon would be a place to do that with some certitude that we get the right answers, with a healthy crew returning from Mars as well as going there. Exploration is an investment in our future, and one to

Fig. 34. ***Human and machine on Mars artist's conception, after 2040. When the first humans venture across the surface of Mars, they may be inclined to collect artifacts from early spacefaring years. Here an astronaut retrieves the Sojourner rover, which arrived on that planet in 1997. (NASA illustration by Pat Rawlings.)***

continue to make, if we want to see a future full of continued hope for our place in the cosmos.

B. Human and Machine in the Solar System (Brent Sherwood)

The space age is just a little more than five decades old, but in those three generations we have seen astounding achievements: moonwalks; robotic emissaries past Pluto; extended tours of the moons of the giant planets. We see awesome vistas, in many wavelengths, almost to the edge of the universe. Sixteen nations built and run a permanently inhabited space station. Despite the risk and cost, the very challenge of spaceflight compels us. So what will the next century bring? Some combination of four visions may well pull us into a spacefaring future: passenger travel, exploration, resource industrialization, and settlement.

1) *Passenger Travel:* Commercial human spaceflight companies are beginning to operate in Earth orbit already. Multiple private firms are building rockets, capsules, and spaceplanes to get passengers to and from space. And the ISS, today's toehold on the orbital frontier, has taught us how to build large platforms and operate them continuously. Combining these capabilities would allow orbital adventure travel, then tourism to orbital resorts, and eventually large numbers of people traveling in space every year—and large numbers of service workers living there to support them. Could passenger travel become the way we evolve to lunar development?

2) *Exploration:* Mars still captivates our dreams as a special place where space science and human exploration would recombine (Fig. 34). The list of technical challenges is long and daunting, far exceeding the capacity of any one nation; a human Mars journey would take 150 times longer than a lunar trip and involve far higher energies. By the time we could dare it, what would exploration even mean? Every rock on Mars would already be mapped, diverse samples already analyzed in Earth-bound labs, and every possible abode of life examined. Would a small, intrepid crew actually begin learning how to live on Mars, paving the way for human settlement?

3) *Resource Industrialization:* Some asteroids contain huge amounts of platinum-group metals, and the Moon has deposits enriched in rare-Earth elements useful for high-tech industries. Closer to home, even Earth orbit offers a vast resource for industrial development: solar energy (Fig. 35). Continuous, inexhaustible, and clean, it could be collected for microwave transmission to Earth's surface. Unlimited electrical power would transform civilization by bringing the third world up to western energy standards,

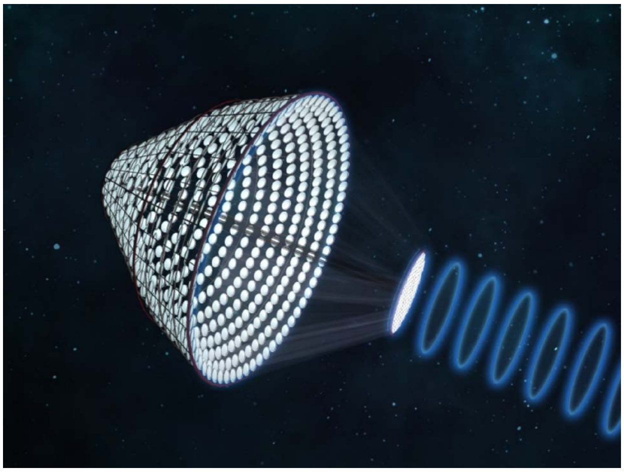

Fig. 35. ***Future space industrialization could provide unlimited clean electrical power to Earth. SPS-ALPHA concept is more efficient, lightweight, and practical than earlier generation space solar power satellite configurations. (Image courtesy Artemis Innovation Management Solutions LLC, (c) 2011.)***

including desalination of clean drinking water from the ocean and production of hydrogen for mobile power. This would require collecting sunlight in geosynchronous orbit at platforms about as large in total as five times the paved area of the U.S. National Highway System. Macro-engineering such infrastructure would be a grand project akin to human Mars missions, combining human spaceflight, advanced robotics, heavy-lift launch, large lightweight structures, energy conversion technologies, and many federal and international agencies. Might humanity's search for energy solutions that avoid societal disruption, regional conflict, and environmental devastation provide a focus for our next century in space?

4) Settlement: If off-world settlement becomes a societal priority, our Moon offers a fourth future: routine back-and-forth exchange of material, equipment, and people using commercial flight providers; development of indigenous construction and outfitting using lunar materials; and establishment of settler families running businesses to support tourism and mining of the rare-Earth elements needed back home for electricity-generator magnets and other specialized uses. Will extending economic activity to the Moon drive our spacefaring goals toward creating a two-world civilization?

All four of these visions are opened and enabled by the further codevelopment of human and robotic spaceflight. Unstructured challenges require human presence, yet humans cannot live or function in space without sophisticated machines. However, that obvious interdependency is only the beginning. Old boundaries are starting to blur with the rise of technologies like bioengineering, nanotechnology, and artificial intelligence. Telepresence brings human sensation, cognition, and manipulation into remote places. Our machines become ever more lifelike. And our very bodies are increasingly enhanced by embedded devices and molecular therapies. By merging what we have been for hundreds of millennia with what we learn to fashion in this century, we would become the explorers and settlers that expand human consciousness outward to inhabit the Solar System. ■

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