The 1990s and Beyond: Big-Time Space Science and New National Security Challenges

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ABSTRACT

The Johns Hopkins University Applied Physics Laboratory (APL) Space Exploration Sector (recently renamed from the Space Department) evolved from focusing mostly on national security needs to including missions in which civilian space assumed a leading role. This transition started in the 1980s but accelerated significantly after the end of the Cold War in the early 1990s. It coincided with the preceding decade's scarcity of medium-class planetary missions, which necessitated a new paradigm of small, science-focused projects that had limited objectives, could be developed and flown in about 3 years, entailed moderate cost, and posed low risk; this paradigm became the Discovery Program. APL was particularly well suited for this type of operation, having worked previously with the NASA Explorer program. Similarly, national security needs evolved from single missions intended to obtain a specific set of measurements, such as the Midcourse Space Experiment (MSX), to multi-spacecraft aggregates employing a new generation of high-level small satellites capable of meeting DoD's and other sponsors' need for reliability, flexibility, and performance at substantially lower costs. This article describes APL's contributions to space science and national security beginning with the start of these changes in the 1990s and continuing to the present.

INTRODUCTION

As described in the article by Fountain et al. in this issue, and also in a previous *Johns Hopkins APL Technical Digest* article,[1] the early years of the Johns Hopkins University Applied Physics Laboratory (APL) Space Exploration Sector were clearly characterized by engineering innovation, with only that degree of science necessary to implement an operational system. During the late 1960s and early 1970s, the seeds of science "for science's sake" had been planted, and the organization's work evolved to support science missions, whether funded by DoD or by NASA. However, the sector remained an engineering organization rooted in its history, with service to the nation's security needs as its principal driver. It was in the late 1970s and early 1980s that science activity in the sector came of age, in the sense that it evolved from isolated instruments and experiments on various missions to addressing significant scientific problems that could be tested by the implementation of an entire mission, including spacecraft, instruments, data analyses, and publication. The first of these missions was the Active Magnetospheric Particle Tracer Explorer (AMPTE) program.

AMPTE's implementation methodology called for a single science and engineering team assembled by a principal investigator (PI) and proposed to NASA a mission to address a scientific objective of paramount importance. The science objective had been prioritized in a National Academy of Sciences report (a precursor to today's decadal surveys); the AMPTE concept was included in one such report[2] under the title of "Active Experimental Techniques," within the programmatic area of Explorers that had been a line item in the NASA budget since Explorer 1. After an open competition prior to the formal publication of the National Academy of Sciences report, NASA selected the project for development, and it was implemented in collaboration with Germany and the United Kingdom (see the article by Fountain et al., this issue, and Refs. 1 and 3) with a 1984 launch. The pioneering aspect of this methodology cannot be overemphasized, for AMPTE became a new paradigm of the so-called PI-class missions—and for good reasons. At a time when space science missions were running about 75% over budget on average and typically overran their estimated development time, AMPTE came in on budget and on schedule and it exceeded its projected lifetime by 4 years.

NASA decided in 1986 to proceed with soliciting other missions under the Explorer line using the same PI-led team concept that had proved so successful for AMPTE. Two missions resulted from this second call for proposals: the Advanced Composition Explorer (ACE), which in essence was an expanded AMPTE-like team with Ed Stone of Caltech as PI and APL as the mission implementation organization, and the Far Ultraviolet Spectroscopic Explorer (FUSE) mission with Warren Moos of Johns Hopkins University as PI and a Hopkins–APL team as the implementing organization (although this was not the initial arrangement; see more below).

Meanwhile, in the 1980s, the nation's planetary exploration program had come to a virtual standstill. The plan to encounter comet Halley during its perihelion in 1986 was scrapped, the Galileo mission to Jupiter had been repeatedly delayed, and the Planetary Observer program, the first spacecraft of which was to be the Mars Observer, had exceeded its original cost goals of approximately $200 million per mission to a cost of well over $500 million due to delays. By the late 1980s, it was clear that a new strategy was required. The Solar System Exploration leadership at NASA headquarters, together with the science community, decided to initiate a series of workshops intended to develop a new strategy for the program. The strategy included reexamining the possibility of a small, low-cost, fast-paced program that would use techniques other than those traditionally employed in planetary missions. Out of the 1989 workshop came a science working group that eventually formulated the elements of the Discovery Program,[4] and it became a line item in the NASA planetary budget proposal to Congress in FY1993. In essence, the PI-class methodology introduced by the Explorer program was now adapted to serve the planetary community, with Near Earth Asteroid Rendezvous (NEAR) at APL as the first mission.

While NASA's culture evolved, so too did that of the national security space community. U.S. Space Command was created in 1985 to support space operations and provide unity of command. While the Air Force controlled the majority of DoD space funding, the Army and Navy both strengthened their space programs throughout the late 1980s into the early 1990s. It is in these decades, however, that APL's sponsorship changed. By 1990, APL's sponsorship by the U.S. Navy had declined. While ballistic missile defense (under the sponsorship of the Strategic Defense Initiative Organization, SDIO/Ballistic Missile Defense Organization, BMDO/Missile Defense Agency, MDA) became a significant part of APL's space activity in the 1990s, it also declined significantly by the decade's end. Space programs were not insulated from the Defense Reform Initiatives of the mid-1990s. By the turn of the century, the organization and management of the United States' space enterprise became a subject of intense study. The Rumsfeld Commission of 2001[5] was formed to comment on the "organization and management of space activities that support U.S. national security interests." However, it went further, noting that "the critical need" is for the highest levels of national leadership to provide guidance and redirection. The study specifically stated that the nation should expect future conflict in the space domain, and investment in science and technology was essential. While APL's role with NASA was moving toward dedicated science missions, its role in national security space came under study. New acquisition practices affected APL's ability to contribute, while the coming small satellite revolution was setting the stage for a new role. By 2000, DoD was betting on the emergence of a microsat revolution.[6] It would take another decade to find that this revolution could meet an important national need.

THE 1990s: A DECADE OF TRANSITION

The 1980s came to a close with the completion of the fast-paced elements of the strategic defense program and the launch of Galileo, the first Jupiter orbiter, with an advanced APL energetic particle instrument evolved from the Voyager design. Figure 1 continues the timeline from the article by Fountain et al., in this issue, into the decade of the 1990s, which began with the launch of Ulysses, the first mission designed to go out of the ecliptic plane and over the poles of the Sun. The APL energetic particle and composition detector on Ulysses made key discoveries on the particle environment at high solar latitudes[7] and continued to function properly until the spacecraft ceased operations in 2009. Other launches

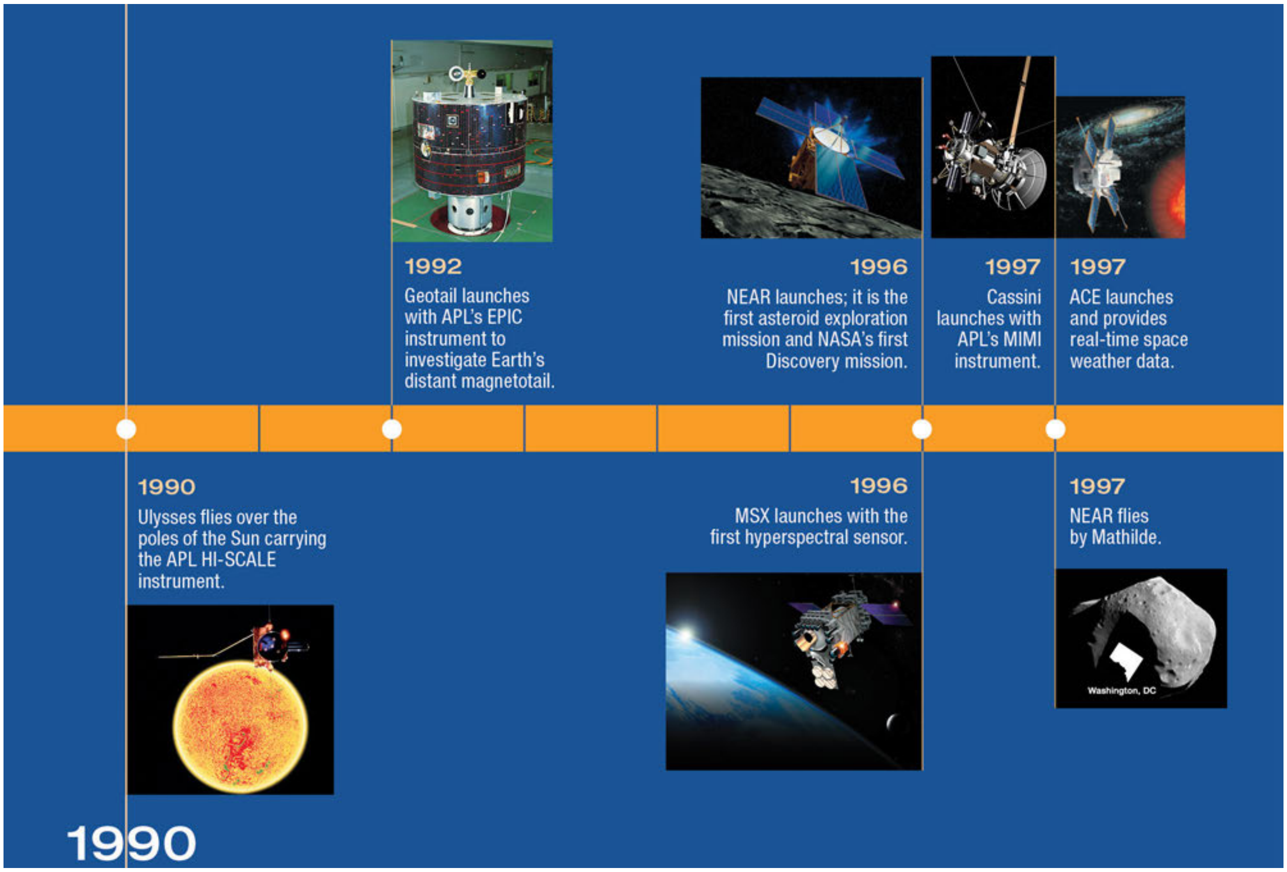

Figure 1. Evolution of space science, exploration, and technology at APL—from national security to heliophysics and planetary exploration.

with APL instruments on board continued through the 1990s: The Japan Space Agency/NASA Geotail mission launched in 1992; it performed the first investigation of Earth's distant magnetotail (~200 R_E) and continues operations to date. A wealth of new discoveries emerged over the years about the dynamics and particle composition[8] and continue to this day. The Cassini–Huygens mission to orbit Saturn launched in 1997, carrying a novel camera[9] that used energetic neutral atoms (instead of photons) to image the plasmas circulating within the magnetosphere of Saturn (see Fig. 3).[10] Most of the work during the 1990s, however, concentrated on designing, building, testing, and launching three complete missions, including several instruments in each case: NEAR, the Midcourse Space Experiment (MSX), and ACE.

As discussed in the introduction, NEAR was the first Discovery mission flown (see Box 1) and set the pattern for the Discovery series. The project development phase came in under the cost cap of $150 million (FY1992 dollars) at $112 million, ahead of schedule in 27 months versus the 36-month requirement, and at low risk versus the "acceptable risk" specification. It was the first mission to validate the "faster, better, cheaper" approach suggested by the then-NASA Administrator Daniel Goldin.[11,12]

BOX 1. THE NEAR MISSION

NASA funded competing studies at APL and the Jet Propulsion Laboratory (JPL) on the definition for the NEAR mission, with a requirement for a total cost not to exceed $150 million in FY1992 dollars. Both studies were completed by May 1991 and were presented at the meeting of the NASA-appointed *ad hoc* Science Definition Team. The studies reached strikingly different conclusions: the APL study estimated that the NEAR mission could be done for about $110 million, while the JPL study concluded that it was impossible for such a mission to come under the $150 million cap set by NASA. By early 1992, NASA had decided to select another mission as the first Discovery mission (the Mars Environmental Survey, or MESUR, Pathfinder, which had been studied at the Ames Research Center), and it assigned JPL as the NASA center to implement it. At the same time, NASA informed APL that NEAR would be the second Discovery mission and would be implemented by APL, with launch in 1998 to rendezvous with the asteroid Eros. NEAR launched first in February 1996, then added a flyby of the asteroid Mathilde, and landed on Eros at the end of the 1-year orbital mission, the latter two phases being beyond the scope of the original requirement.

APL began building its 55th spacecraft late in 1988 for MDA (then BMDO). MSX was a follow-on mission to the highly successful groundbreaking Delta 180 series of flight programs for the MDA (then known as the SDIO before becoming the BMDO). It was launched in April 1996. MSX would successfully complete its research mission in the first year, at the end of which the cryogenics needed for its long-wavelength optical instrument were consumed. Its other instruments remained operational, allowing it to become a space-based surveillance platform meeting U.S. Air Force operational needs. It was transferred to Air Force Space Command in October 2000 as the nation's first Space-Based Space Surveillance system, meeting an operational need until decommissioning in June 2008 (see Box 2).

BOX 2. THE MSX MISSION

MSX was designed to make simultaneous calibrated, optical measurements over a wide range of wavelengths in support of the MDA mission.[13] A second program goal was to transfer technology to other programs with similar requirements. It bore a suite of sensors including a cryogenic scanning radiometer (the cryostat was solid hydrogen, the first ever flown in space) and a Fourier transform spectrometer, visible and UV imagers and spectroscopic imagers, and a set of instruments to monitor contamination. The optical payload covered the far UV (110 nm) through the long-wave IR (28 μm). The satellite was a very nimble, long-duration, "observatory"-style measurement platform. Its primary purpose was to collect and analyze target and background phenomenology related to the MDA midcourse sensor requirements. As a carefully calibrated instrument, MSX also supported civil studies involving terrestrial and atmospheric remote sensing and astronomy.

Figure 2. The MSX spacecraft, carrying the first-ever solid hydrogen IR detector cooling system launched into space, in fully tested flight configuration.

ACE was launched successfully in August 1997, the third complete mission APL's Space Department sent into orbit within a period of less than 19 months. It contained a full complement of instruments designed to delineate the mass, charge, and isotopic composition of galactic and solar matter with unprecedented accuracy. The instruments covered 10^6 in energy, from the solar wind (a few electronvolts) to galactic cosmic rays (several gigaelectronvolts), and a combined 10^{14} in intensity.[14] The spacecraft was positioned at the L1 libration point, a distance of ~1.5 million kilometers upstream of Earth in the direction of the Sun, and thus located in an ideal position to intercept solar energetic particles and coronal mass ejections emitted by the Sun and propagating toward Earth. Thus, in addition to its purely scientific mission, ACE was equipped with detectors whose output was monitored in real time and could provide warning of up to 1 hour on the arrival of solar "weather fronts" at Earth. ACE has been the world's first, continuous, real-time space weather station and has been performing this service for NOAA (and the U.S. Air Force/Air Force Weather Agency) for more than 19 years (see http://www.swpc.noaa.gov/products/ace-real-time-solar-wind).

The success in the development of NEAR and ACE in the 1990s, on schedule, under cost, and reaching full technical performance achievements throughout, motivated NASA management to view APL as a partner that could address and solve problems in other parts of the agency. NASA had canceled the FUSE mission that was being developed at Goddard Space Flight Center because of repeated cost overruns. Nevertheless, the FUSE science was an important decadal objective, and there was an effort to revive the program within a cost cap. NASA headquarters asked whether APL could work with the Homewood Campus of the university to prepare a plan that would deliver the FUSE science for $100 million or less. A management scheme was established whereby the campus PI (Warren Moos) would work with APL to develop a spacecraft that would meet the science requirements. This was done successfully; FUSE launched in 1999 and collected data for the next 8 years.[15]

THE 2000s: A MIX OF HELIOPHYSICS AND PLANETARY MISSIONS

The Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) project was another problem NASA management faced in the mid-1990s. This first mission of the Solar Terrestrial Probes Pro-

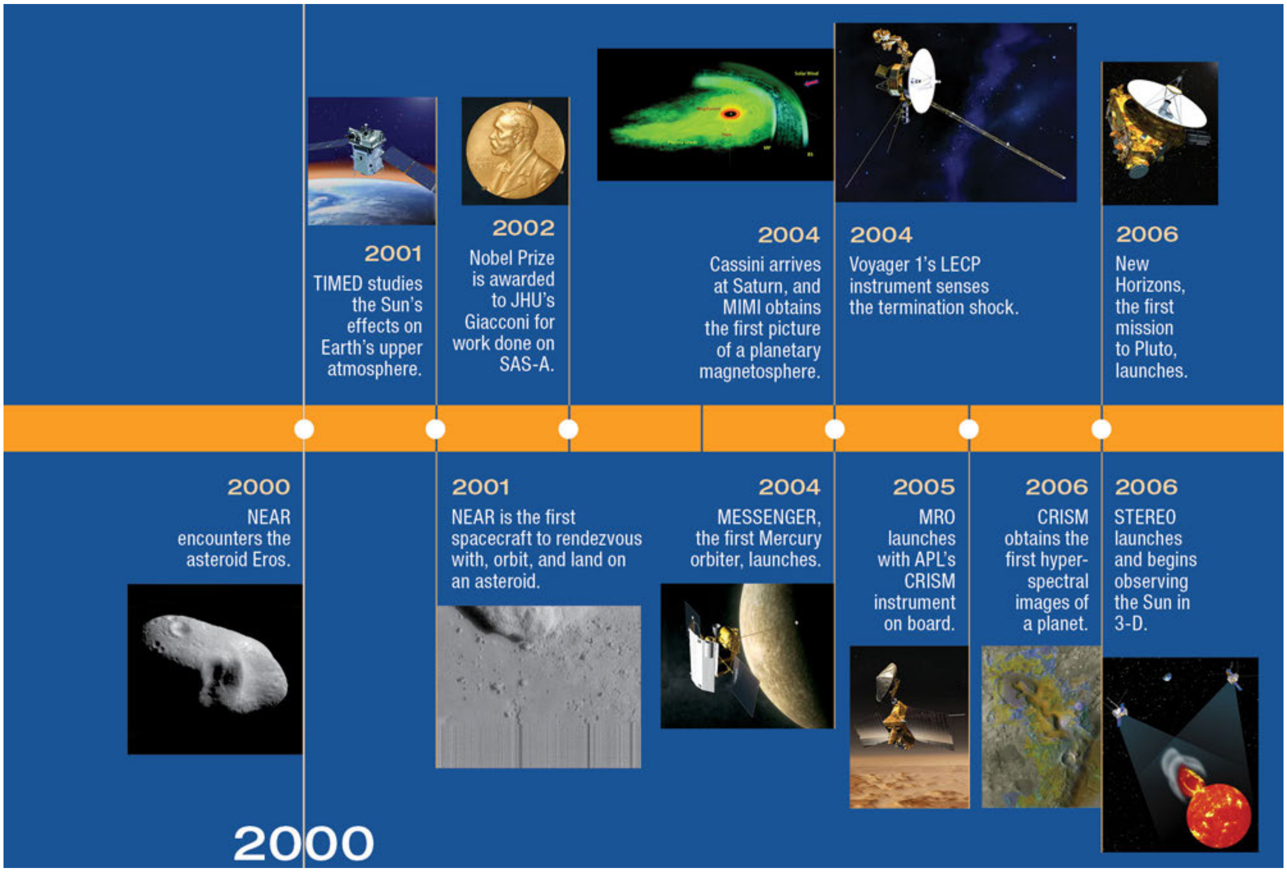

Figure 3. Evolution of space science, exploration, and technology at APL—the blossoming of full missions in planetary exploration and heliophysics in the first decade of the new century.

gram (STPP) line was in danger of cancellation in 1994 because the mission had grown to over $400 million for the two spacecraft. In view of the possible demise of the program, Dr. Wes Huntress asked APL if it could design a mission that would retain 80% of the science while adhering to a capped cost of $100 million. After a 4-month study, the Lab concluded that this was possible and, after an extended study period of the instrument payload, the project was assigned to APL for full development in 1997. The launch was in late 2001, with the delay due to the late delivery of the Jason spacecraft co-manifested on the same launch vehicle. To this day, the mission has been producing high-quality data, including UV imagery of Earth with GUVI and information on the Sun's influence on Earth's upper atmosphere. The mission and its findings are detailed in over 2000 publications in the refereed literature, 48 book articles, and innumerable presentations in conferences.[16]

The first decade of the new century was an exceptionally busy time for APL's Space Department (Fig. 3). The Comet Nucleus Tour (CONTOUR) spacecraft was in development, as was the first Mercury orbiter (Mercury Surface, Space Environment, Geochemistry, and Ranging, or MESSENGER), while the twin-spacecraft STEREO (Solar Terrestrial Relations Observatory) mission was getting ready to obtain the first stereoscopic images of solar eruptions. In addition, several instruments were in development for each of the missions. Despite all the work, many in the management team and staff were strongly motivated to propose a mission to Pluto, because it had seemed that such a mission may never materialize in other NASA centers because of the technical difficulties and the projected large costs. So a team was put together to propose New Horizons and, after much heated competition, the APL–Southwest Research Institute team won, and the rest is history.[17]

The external environment was favorable for APL as the first decade started because NEAR had been placed into orbit around Eros in February 2000, despite a mishap a year earlier that had forced an extra orbit around the Sun. After the 1-year orbital requirement was completed, the team decided to ask NASA for approval to use the remaining ~6 kg of fuel to attempt a controlled descent to the surface. This was achieved successfully on February 12, 2001, and the spacecraft not only provided imaging data down to an altitude of ~130 m but also continued to operate on the ground and transmit data for the gamma-ray spectrometer for the following 2 weeks, providing the best composition data obtained of a planetary (asteroid) surface until that time. Data collection was discontinued and operations ended as there was no additional science to be gained from the landing area. The NEAR mission made history as the first orbiter of an asteroid but also the first lander on a small body, even though it was never designed for that purpose. Also, the seeds planted long ago came to fruition, in that Hopkins professor Riccardo Giacconi, the PI of SAS-A (Uhuru), which launched in 1970 (see the article by Fountain et al. in this issue), won the 1992 Nobel Prize in Physics for his work in the discovery and mapping of the X-ray sky.

As is often the case, however, the euphoria was marred by the loss of the CONTOUR mission in 2002, some 6 weeks after a successful launch and initial operations in Earth orbit. When the command was transmitted to fire the solid-state kick stage to inject the spacecraft to its programmed interplanetary orbit, contact was lost and never regained. An APL Failure Review Board, using data from both public and classified sources, established that the kick stage exploded and destroyed the spacecraft. The equivalent NASA Mishap Investigation Board identified four possible causes for the failure but concluded that the probable proximate cause was structural failure of the spacecraft due to plume heating during the embedded solid-rocket motor burn.[18] The CONTOUR mission, however, also stayed within the programmed cost and schedule. Perhaps the acquisition and test-firing of a second solid-rocket motor may have prevented the failure, since the flight motor was "recertified by the manufacturer," but concerns about staying within the budget cap prevented purchasing a test unit, a $5 million

BOX 3. THE MESSENGER MISSION

The principal design driver for MESSENGER was the thermal environment. An overview of the schematic shows the basic features of the overall design.[19] A ceramic-fabric sunshade, heat radiators, and a mission design that limited time over the planet's hottest regions protected MESSENGER without expensive and impractical cooling systems. The spacecraft's graphite composite structure—strong, lightweight, and heat tolerant—was integrated with a low-mass propulsion system that efficiently stored and distributed the approximately 600 kg (~1320 lb) of propellant that accounted for 54% of MESSENGER's total launch weight, the largest such ratio of any spacecraft until that time. The combination of the sunshade, thermal blanketing, and heat-radiation system allowed the spacecraft to operate without special high-temperature electronics. MESSENGER's X-band coherent communications system included two high-gain, electronically steered, phased-array antennas, the first ever used on a deep-space mission; two medium-gain fanbeam antennas; and four low-gain antennas. The circularly polarized phased arrays, developed by APL and located with the fanbeam antennas on the front and back of the spacecraft, were the main link for sending science data to Earth.

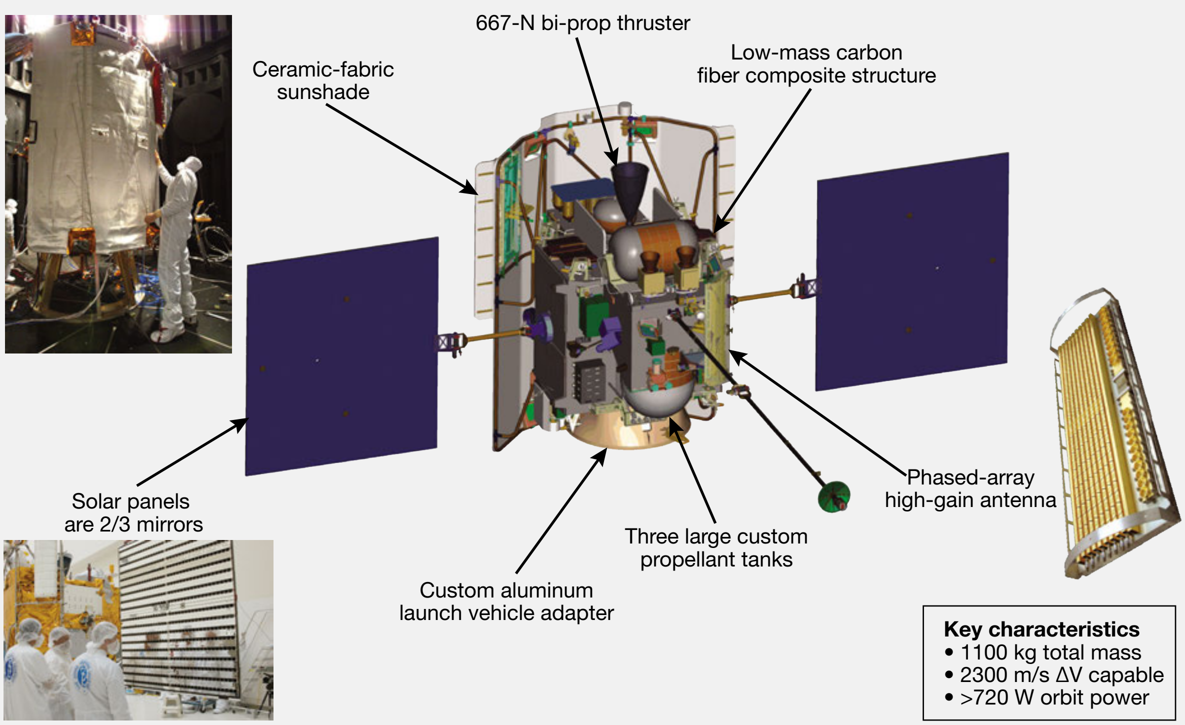

Figure 4. MESSENGER schematic highlighting the most challenging elements required for an orbiter of Mercury where solar input is 11 times that at Earth.

expenditure at that time. It is important to note that a similar solid-rocket motor had been used successfully on AMPTE, but that motor was new and a test-firing was performed with an identical rocket before launch.

The biggest challenge of this decade was the design, building, assembly, and testing of the MESSENGER orbiter for Mercury. Design studies performed previously by NASA in the late 1980s suggested price tags well in excess of $1 billion. APL had proposed and was selected for this mission within the cost cap of Discovery, then at ~$400 million. Although previous missions had perihelia at the orbit of Mercury (Mariner 10 and Helios 1 and 2), none had orbited the planet where the heat input from the Sun was 11 times that at Earth, and the planetary IR emissions from below were just as formidable. The design challenges were overcome (see Box 3) and MESSENGER made remarkable discoveries,[20] such as polar ice deposits, in a mission that exceeded its initial 1-year requirement by 3 additional years.

In December 2004, an event of historic significance took place when the Voyager 1 spacecraft crossed the heliospheric termination shock (TS) at a distance of 94 AU (1 AU equals 150 million kilometers, the distance between Earth and the Sun), carrying APL's Low Energy Charged Particle (LECP) instrument that had been observing precursor ion events for the previous 2 years.[21] The distance of the TS from the Sun had been modeled for the past few decades with predictions ranging from five to several tens of astronomical units, and it was finally observed much farther out than had been anticipated. Further, the long-predicted source of anomalous cosmic rays at the TS was not observed, just one of the many theoretical models that the Voyager observations upended in this uncharted region of space. The following 7 years of traversal of the heliosheath (the region between the TS and the heliopause) revealed a reservoir of very hot (tens of kiloelectronvolts) plasma that extended up to the boundary of the solar atmosphere with the galaxy, as explained later.

Figure 3 also notes the launch of the Mars Reconnaissance Orbiter (MRO), which included the APL-built Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument, the first hyperspectral (564 channels) imager flown on a planetary mission. CRISM detects minerals formed by flowing liquid water, among other compounds, and has been instrumental in delineating the presence of water on Mars. It is important to note that CRISM evolved[22] from a similar instrument design that was flown on the MSX spacecraft in the 1990s (see Box 2). This is just one example of the synergy between defense and civilian technology transfer at APL that has occurred routinely over many years and among various programs.

The development of New Horizons[23] represented a challenge opposite that of MESSENGER, in that the thermal environment of Pluto was at the low end of the scale (–232°C versus 426°C). This environment was not nearly as difficult since good thermal design techniques in retaining heat had been used routinely on spacecraft such as Voyager with great success. The principal challenge in this case was the requirement of a radioisotope thermoelectric generator (RTG) power supply because of Pluto's distance of some 33 AU from the Sun. This meant two things: first, identifying an appropriate RTG that would produce at least 180 W; and second, obtaining regulatory approval (per Presidential Directive NSC-25) for launch in less than 4 years. Note that for the preceding flight mission (Cassini) using RTGs, it took 8 years to obtain launch approval. Obviously, both challenges were overcome, and New Horizons launched on schedule on January 19, 2006, flying by Jupiter in February 2007 and then by Pluto on July 15, 2015.

The fourth complete spacecraft built by APL in the first decade of the 21st century was for the STEREO mission, consisting of two near-identical orbiters in heliocentric trajectories, launched in October 2006 (Fig. 3). STEREO offers a totally new perspective on solar eruptions by imaging coronal mass ejections and background events from two identical spacecraft simultaneously.[24] One spacecraft leads the Earth in its orbit and one lags behind, each carrying a cluster of instruments. When combined with data from observatories on the ground or in low Earth orbit, these data allow one to track the buildup and liftoff of magnetic energy on the Sun and the trajectory of Earth-bound coronal mass ejections in 3-D. It is a key step in building up the capability for monitoring and eventually predicting space weather.

Thus, APL has been involved in the first space weather monitor (ACE) and continues to lead the evolution to an eventual operational system with STEREO.

THE 2010s: A MIX OF NATIONAL SECURITY SPACE, EARTH'S ENVIRONMENT, AND OPERATIONS

Although NASA missions pretty much dominated the Space Department's work in the 2000s, various studies and small projects were in progress to define and exploit new technologies, especially microsats and minisats in the overall defense space environment. These efforts appeared to bear fruit in the late 2000s and the 2010s (Fig. 5). In the 1990s, the Air Force had identified a need for a space-based radar system. Such a system had not been realized at that time, but an opportunity presented itself because the technology finally appeared ready. An industry–government team formed to develop a series of mini-RF (short for miniature radio frequency) instruments of increasing capability and to fly them on three successive missions, demonstrating their technology.

Mini-RF successfully flew on the first two missions as planned. First, an instrument flew on the Indian Space

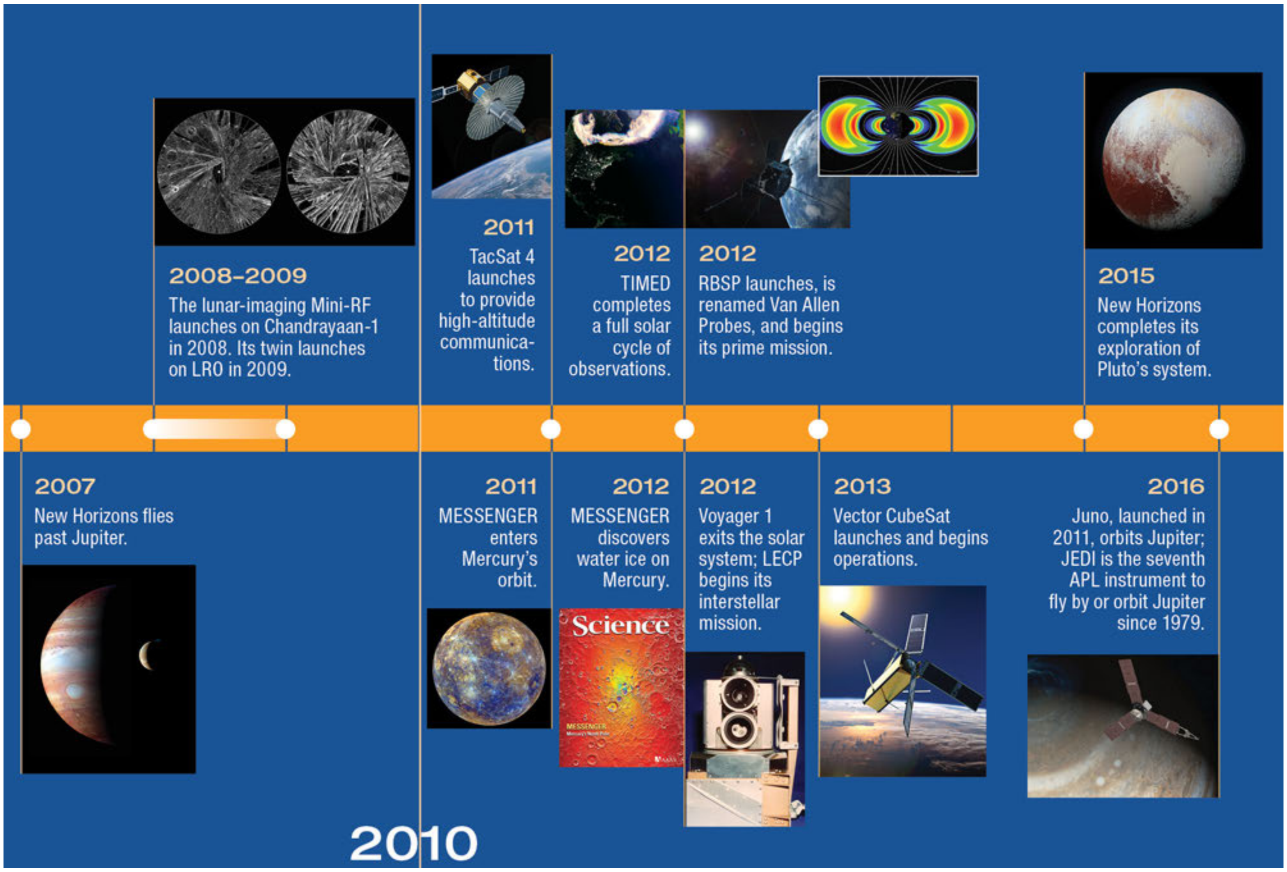

Figure 5. Evolution of space science, exploration, and technology at APL—national security and the CubeSat era. The building and launching of the Van Allen Probes and the Pluto flyby have marked a challenging decade so far.

Research Organisation's Chandrayaan-1's lunar orbiter as Mini-SAR (short for Miniature Synthetic Aperture Radar), launched in October 2008. An enhanced version of the instrument next flew on NASA's Lunar Reconnaissance Orbiter (LRO), launched in June 2009. Finally, early plans were to fly it on a tactical satellite (TacSat) for the National Reconnaissance Office; however, other program priorities caused this third mission to be scrapped. Mini-RF spent 18 months successfully mapping the moon on LRO, far surpassing requirements for science data acquisition by providing more than 38 TB. Mini-RF collected more than 2000 strips of survey data covering about two-thirds of the lunar surface. This included 98% of the lunar polar regions. The lunar far side (the dark side of the moon) had never been imaged by radar before LRO. Mini-RF achieved this first and also imaged the floors of permanently shadowed impact craters that cannot be seen from Earth.

In 2007, the Air Force founded the Operationally Responsive Space (ORS) Office at Kirtland Air Force Base. Under its leadership with the Office of Naval Research, a joint APL–Naval Research Laboratory (NRL) team developed the TacSat 4 spacecraft, which hosted the NRL COMMx (Advanced SATCOM Experiment) payload. The mission launched in 2011, successfully demonstrating the value of the integrated systems engineering team (ISET), which provided a technical, nonproprietary construct for government, laboratory, and industry to establish standards and cost, schedule, and performance metrics. The spacecraft was fabricated by NRL and APL and built to the ISET-established TacSat standards. It was completed under NRL program management and APL systems engineering by the end of 2009. Although a smallsat, TacSat 4 is equipped with a large 3.8-m antenna for UHF communications channels. These channels can be used for communications, data exfiltration, or blue force tracking. The spacecraft is in a highly elliptical (Molniya-like) orbit, capable of providing hours of communication periods per orbit. TacSat 4 also demonstrated rapid relocation and tasking to different theaters of operation.

As DoD was placing bets on a small satellite revolution by investing in microsat technology, the academic community was embracing nanosats that are even cheaper and faster to develop.[25] These CubeSats typically come in units of 10 × 10 × 10 cm form factor (1 U). Having proven that useful CubeSat mission concepts exist and that they can dramatically lower costs to sponsors, APL introduced a new generation of CubeSats capable of meeting high reliability requirements. The

Figure 6. TacSat 4, a smallsat with a large (3.8-m) antenna, demonstrated a new era in UHF communications.

APL CubeSat draws from five decades of APL experience in building rugged spacecraft for harsh environments near and far from Earth—and from the Lab's deep, unique understanding of spacecraft, aerospace, and applied engineering techniques. The satellites pursued under the Multimission Bus Demonstration (MBD) project have all the subsystems of a standard orbiter—attitude control, command and data handling, communications, navigation, power, and payload—scaled to fit into a 34 × 10 × 10 cm (~3 U) package that weighs less than 5 kg. In designing the CubeSats, APL developed an excellent understanding of what the subsystems industry was able to provide and what it was not able to provide.

In November 2013, two of APL's CubeSats were among 29 satellites launched to orbit aboard a Minotaur I rocket (as part of NASA's ELaNa IV, or Educational Launch of Nanosatellite) from Wallops Flight Facility, Virginia. These MBD spacecraft were designated ORS Tech 1 and ORS Tech 2 for this launch. After 18 months in orbit—months longer than typical for spacecraft in their class—the twin ORS Tech 1 and 2 CubeSats succumbed to atmospheric drag and completed their journey. By the time atmospheric drag caught up to the spacecraft, they had completed one of the longest operational periods ever for a CubeSat.

Beyond the national security and CubeSat efforts, the principal focus of APL's space enterprise was building the Radiation Belt Space Probes (RBSP), renamed the Van Allen Probes soon after launch in honor of the scientist and APL alumnus James A. Van Allen who discovered the radiation belts surrounding Earth. These doughnuts of radiation, shown schematically in Fig. 5, consist of highly penetrating protons (with energies of 10–600 MeV) in the inner belt and similarly penetrating (up to 10 Mev) electrons in the outer belt. Many civilian and national security spacecraft, such as GPS, operate in these altitudes, and their survival depends on detailed knowledge of the intensities and variability of this trapped radiation.

The mission's primary science objective is to provide understanding, ideally to the point of predictability, of how populations of relativistic electrons and penetrating ions in space form or change in response to variable inputs of energy from the Sun. The instruments on the two Van Allen Probes spacecraft provide the measurements needed to characterize and quantify the processes that produce relativistic ions and electrons. They measure the properties of charged particles that make up Earth's radiation belts and the plasma waves that interact with them, the large-scale electric fields that transport them, and the magnetic field that guides them.[26]

The launch took place on August 30, 2012, and the two spacecraft have been producing a wealth of data ever since. Among the more surprising findings is the formation of a third, temporary, belt that appears as a result of large geomagnetic disturbances[27] driven by coronal mass ejections, as detected by other spacecraft, such as ACE and STEREO, outside the magnetosphere. The importance of these measurements to the emergent requirement of understanding, mitigating, and eventually forecasting space weather events cannot be overemphasized. And what a marvelous narrative that completes the circle of the history of this institution: it begins with James Van Allen coming to APL in the 1940s and doing high-altitude research with V-2 and Aerobee rockets and then moving on to the University of Iowa and discovering Earth's radiation belts, and it ends with APL building the spacecraft that bear his name to study the Van Allen belts in detail.

Beyond the launch of Van Allen Probes, however, the event that marked August 2012 for APL, and indeed the world, was one that occurred in the far reaches of the solar system, namely Voyager 1's crossing of the boundary between the atmosphere of the Sun (heliosphere) and the galaxy,[28] at a distance of 18.2 billion kilometers or 97 AU (1 AU = 150 million kilometers, the distance between Earth and the Sun). Voyager 1 was the first and, to this date, the only messenger from the human race to the galaxy. The journey had taken 35 years, was full of surprises, and represented an odyssey that is unlikely to be matched for at least the next generation. What is also remarkable is that the stepper motor in LECP, which rotates the detector platform once every 192 seconds and was designed for a 4-year mission to Jupiter and Saturn and tested to 500,000 steps, is still rotating to this day, having stepped over 7 million times.

The most memorable event of the second decade of this century so far, for APL and probably for NASA too, is the New Horizons spacecraft's flyby of Pluto in 2015. The Pluto encounter, in completing NASA's exploration of the last classical planet 50 years after the Mariner 4 encounter with Mars, was hailed throughout the country and the world and listed among the top-10 science accomplishments of 2015. The first set of results were published just 3 months after the flyby.[29] New Horizons revealed that Pluto has an exceptionally varied surface with a fascinating geology totally unexpected by the planetary science community.[30] The spacecraft is now targeting a January 1, 2019, encounter with a small Kuiper Belt object, KBO 2014 MU69. It will perform the first characterization of a small Kuiper Belt object, one of the thousands that reside in this part of the solar system.

Finally, in 2016, the Juno spacecraft,[31] after a 5-year journey, was placed successfully into a polar orbit about Jupiter, carrying the APL Jupiter Energetic Particle Detector Instrument (JEDI). JEDI is the eighth APL-built instrument to encounter Jupiter, beginning with the two Voyagers in 1979 and followed by Ulysses (twice), Galileo, Cassini, and New Horizons. Many new discoveries are already coming from this polar region of Jupiter's magnetosphere, never before explored.[32]

WHAT THE FUTURE HOLDS

Figure 7 continues the timeline into the next decade and foresees the launch of Space-based Kill Assessment (SKA) sensors in APL's Assured Space Operations Program Area in the National Security Space Mission Area. The program will be a network of small sensors hosted on commercial satellites. The sensors collect the energy signature of the impact between a threat ballistic missile and an interceptor of the Ballistic Missile Defense System. The MDA recognizes that this novel technical approach is a significant way to reduce the overall cost while providing a resilient capability. SKA is a real-world demonstration of the benefits of disaggregation, leveraging existing capital investment and discouraging custom command and control that can require excess infrastructure and personnel. The network of SKA sensors is expected to be on orbit in 2017.

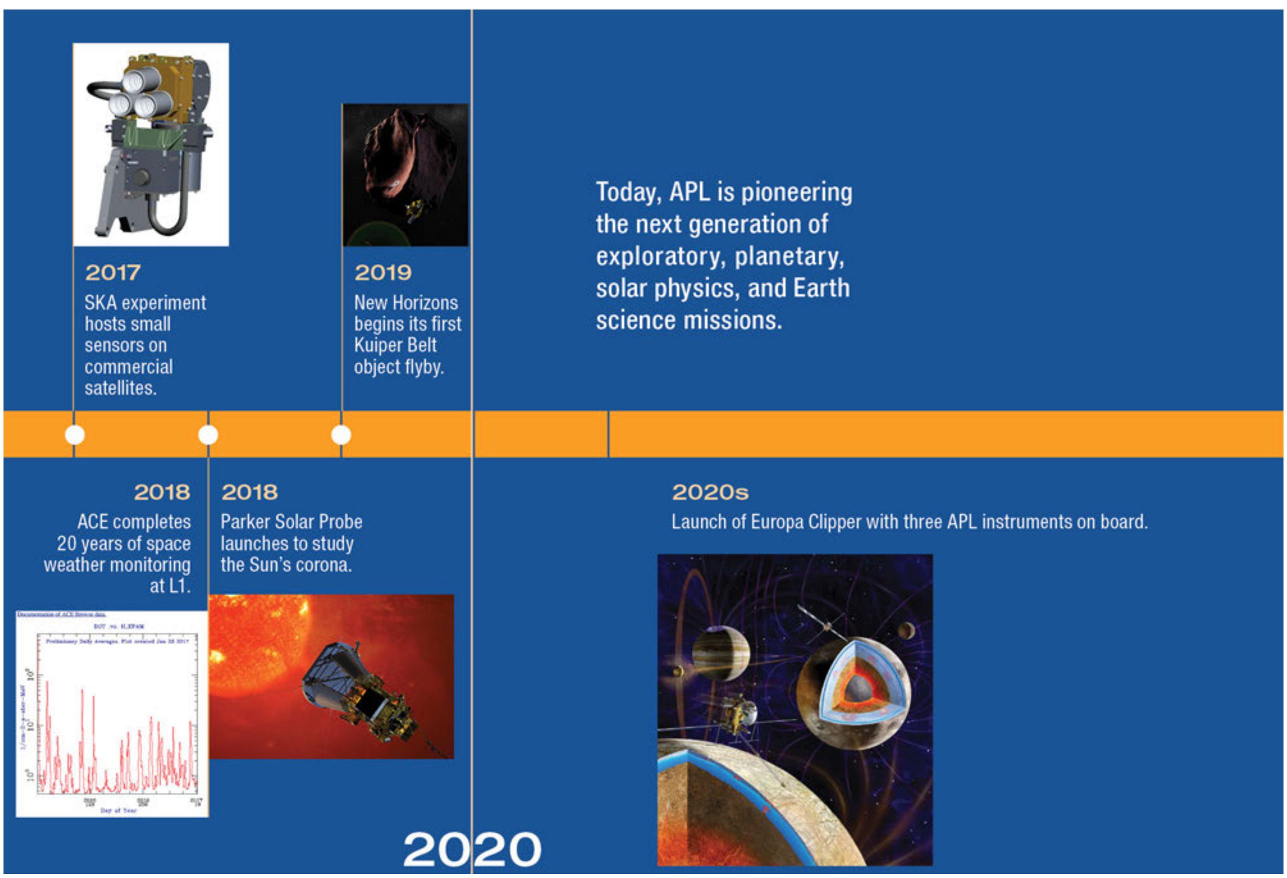

Figure 7. Evolution of space science, exploration, and technology at APL—Parker Solar Probe, a most ambitious NASA project referred to as the mission to a star, is a bookend to APL's missions of fire and ice (i.e., from the Sun to Pluto and beyond).

APL has navigated the sweeping change of the 1990s and beyond. Our historical focus on small, highly capable satellites and low-cost space systems was good preparation for the microsat revolution. Whether the systems weigh a few kilograms or hundreds, APL is ready to support the national security space community with innovative low-cost demonstrations of new capabilities. Further, our disciplined application of systems engineering serves DoD and the intelligence community through a variety of studies and analyses. Our focus has moved from a specific mission platform to a capability, from integrated to fractionated, from dedicated to hosted, and from controlled to automated. And while our work and expertise in sensors is as strong as ever, we are now very capable in the realm of information and its protection.

The Space Sector's principal task at the present time is fabrication, assembly, test, and launch of Parker Solar Probe (formerly Solar Probe Plus), the most ambitious mission ever undertaken by APL. The idea for such a mission goes back to the late 1950s. It had been studied intermittently for some 40 years and, despite its incorporation as a main element in the National Academy's study[33] in 1985, it languished in inconclusive technical trade-offs until assigned to APL in 2002. The current concept was adopted in 2008 and envisions using seven Venus gravity assist flybys to lower the perihelion to ~6.2 million kilometers over a period of nearly 7 years. At closest approach, the spacecraft will be subjected to an intensity of 475 suns, and the heat shield temperature will reach 1377°C, more than the gray iron melting point of 1204°C. The experiments selected for Parker Solar Probe are specifically designed to solve two key questions of solar physics: (*i*) why is the Sun's outer atmosphere so much hotter than the Sun's visible surface? and (*ii*) what propels the solar wind that affects Earth and our solar system? It is expected that the launch of this pioneering mission to a star will take place on schedule in July/August 2018.[34]

The final major mission currently in the design phase is Europa Clipper. While it was always part of NASA's program, with the turn of the 21st century, the emphasis on the search for life and potentially habitable environments beyond the Earth has increased dramatically. Recommended as a top priority in several National Academy studies,[35] a mission to the Jovian moon Europa has long been of great interest, but affordable concepts were lacking. With its thick water ice crust believed to shelter a salty water ocean, Europa is of great interest because it could enable understanding not only of the processes that formed it but also of how it continues to reform a dynamic surface and maintain a liquid ocean. Hubble Space Telescope[36] observations of plumes thought to be water ejected from the ocean through the crust have only increased interest in this "ocean world." APL has partnered with JPL to formulate affordable mission concepts to develop and launch the mission. The spacecraft is designated the Europa Clipper for its innovative mission design that affordably meets the science objectives, and the APL–JPL team has successfully completed the technical reviews required to enter the preliminary design phase in early 2017, on target for a launch in the early 2020s.

CONCLUDING REMARKS

> Your task is not to foresee the future, but to enable it.
>
> —Antoine de Saint Exupéry

Whether one chooses to date from October 24, 1946, the acquisition of the first image of the planet Earth taken from space, or March 5, 1948, the first launch of an Aerobee rocket carrying instruments for cosmic radiation research, APL has a long and rich history of innovation and taking first steps and opening pathways for the expansion of knowledge and capability. Those

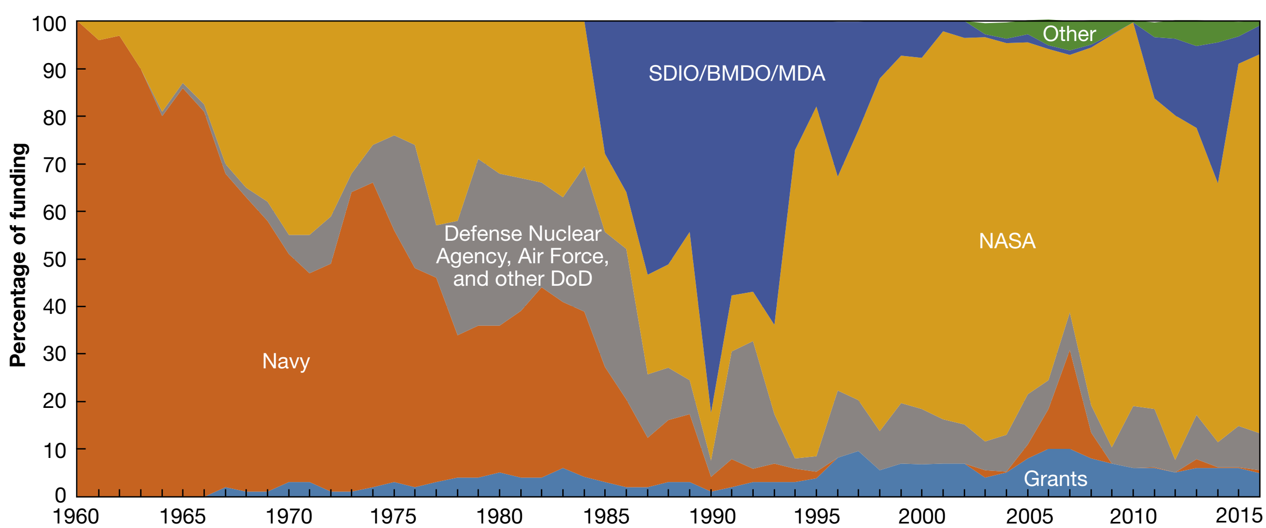

Figure 8. Evolution of space science, exploration, and technology at APL—Space Exploration Sector sponsor history.

first measurements of Earth's radiation environment led to today's vibrant study of the Sun–Earth connection and space weather warning and forecasting capabilities that protect lives and our economy. The curiosity-driven measurements of the Doppler shifts of the radio transmissions from Sputnik led to the first satellite navigation system and a future in which one cannot imagine living without ubiquitous space-based position, navigation, and timing capabilities. The drive to meet a compelling national need led to the first space missile defense demonstrations and space-based sensing for missile defense. The same spirit of innovation led APL to pioneer new effective and affordable approaches to radically increase the pace of exploration of the solar system. The first asteroid rendezvous and dramatic advances in human knowledge from the surface of the Sun to Mercury to Pluto are only a few of the benefits.

While the pioneers in each of these efforts and many other similar ones knew they were working on critical challenges, none of them could have fully predicted the richness of the futures they were enabling, or the details of the pathways to get there. Over the nearly six decades since APL's space enterprise was created, the needs of the nation have changed many times, sometimes very quickly, as shown in Fig. 8. Many other organizations have succumbed to such challenges, unable to reinvent themselves to thrive in a different future. APL met each new challenge with creativity and determination, and in our 75th year, we are poised to yet again make the kinds of critical contributions to critical challenges for which APL is renowned.

Blazing new pathways to previously unimaginable futures requires curiosity and innovation but must be founded on a bedrock of world-class expertise. Defined by systems thinking and a relentless focus on results, APL's culture embodies these tenets and provides the structure and discipline to succeed in overcoming daunting challenges and opening pathways for others to follow. To paraphrase Theodore von Kármán, the people of APL both explore the world that is and create the world that never was. Space is not the final frontier but the "forever" frontier, and APL will continue to be a driving force in pushing the frontiers of knowledge and capability outward.

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