Small Satellite Missions for Planetary Science

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ABSTRACT

The National Aeronautics and Space Administration's Science Mission Directorate is committed to developing science missions based on small-format spacecraft, including CubeSats and those that can be launched from a standard evolved expendable launch vehicle (EELV) secondary payload adapter (ESPA) ring. This paper describes the investments in small-format spacecraft (SmallSats) that NASA's Planetary Science Division has made to date, including nineteen concept studies used to determine if deep space SmallSat missions could credibly conduct high quality science. The results of those studies were used to solicit SmallSat missions under the Small Innovative Missions for Planetary Exploration (SIMPLEx) program. This paper describes these previous investments and the types of technologies needed to accomplish them, and describes the Planetary Science Division's plans to continue developing these small but powerful missions.

INTRODUCTION

NASA's Science Mission Directorate (SMD) recognizes the ability of small spacecraft to conduct compelling science and is now operating 15 science missions using spacecraft smaller than 50 kg each. The names of these missions are shown graphically in Figure 1, where the color of the font indicates the type of science being done by the missions. Ten of them are conducting Earth science, four (CERES, ELFIN, SORTIE, and MINXSS-2) are studying the sun, and one (HALOSat) is an astrophysics mission. All of them orbit the Earth. Similarly, the SMD SmallSat missions under development for future operations are again dominated by Earth-orbiting missions, with many Earth science and heliophysics missions. A notable exception: The Mars Cube One mission (MarCO) terminated operations in January 2019, and was the first SMD CubeSat mission operating in deep space. Of the two planned Planetary Science missions, one, Q-PACE, will operate in Low Earth Orbit (LEO) but LunaH-Map will travel to the Moon. NASA's Heliophysics Division expects to soon send small spacecraft to the Earth-Sun Lagrange Point 1 but selections have not yet been announced. Also, an announcement of a new deep space mission for planetary science is expected soon under the SIMPLEx program, as described below.

Beyond SMD, both the Human Exploration and Operations and Space Technology Mission Directorates (HEOMD and STMD) at NASA are also developing CubeSats relevant to planetary science, including technology demonstrations. While most of these missions are designed for operation in Earth orbit, several will travel to the Moon as secondary payloads on NASA's first launch of the Space Launch System, Artemis 1 (formerly known as Exploration Mission 1, or EM-1). In addition, the international community is actively developing small spacecraft for deep space operation. Japan deployed the 59 kg Procyon probe with the Hayabusa mission in 2014, and the Chinese sent the Luojia-1 CubeSat to the moon in 2018. Several international CubeSats are also scheduled to be launched with the Artemis 1 mission.

Noting these exceptions, the preponderance of these very small spacecraft missions target operation in LEO. There are two primary reasons for this. First, the number of launches to Earth orbit is vastly larger than the number to Earth escape and so the number of opportunities for ride shares as secondary payloads is much higher for Earth-orbiting missions. Second, and a bit circularly, since the market for deep space missions is small, the technologies needed for deep space transportation and operations are not as well developed as those needed for commercial and military applications in Earth orbit.

Nonetheless, the opportunity for exciting science in deep space at a fraction of the cost of traditional missions has compelled NASA's Planetary Science Division (PSD) to develop small spacecraft missions that can conduct planetary science. The following sections describe work that has been done to develop these missions as well as future plans.

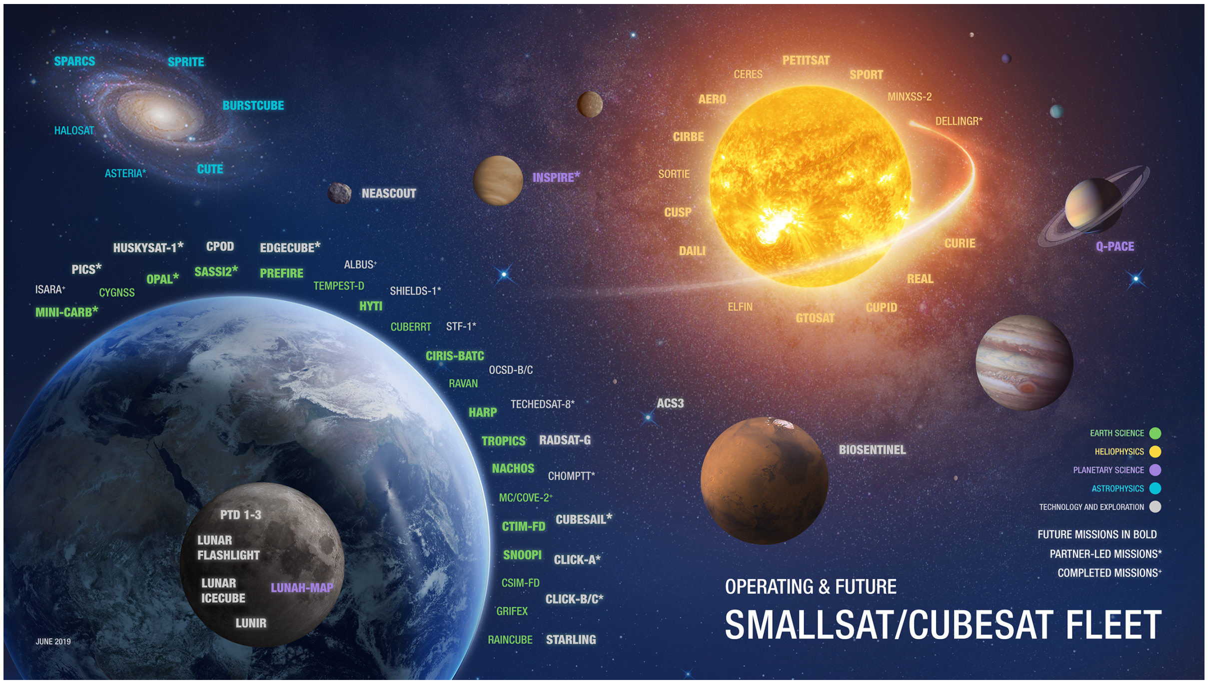

Figure 1: NASA SmallSat missions, including those under development (bold font) and those currently operating (regular font)

CUBESATS FOR PLANETARY SCIENCE

Just as for large missions, PSD has two primary means to develop SmallSat missions: through competed or directed work. In addition, PSD can partner with other organizations who can contribute SmallSats to be launched as secondary payloads on NASA missions to conduct mutually beneficial science. PSD is using all of these approaches, as described below.

Astrobiology CubeSats

In 2007 PSD's Astrobiology Science and Technology Instrument Development (ASTID) program solicited concept studies for small satellite missions relevant to astrobiology. Mission concepts were limited to spacecraft with a total mass less than 50 kg. Selections included the GraviSat by Antonio Ricco at the NASA Ames Research Center to study microorganisms and cells in microgravity, the Exposure of Organics on a Small Satellite (EOOSS) by Orlando Santos, also at Ames, and a Nanosatellite concept to find transiting earth analogs around the brightest Sun-like stars by Sara Seager of the Massachusetts Institute of Technology.

The next year, PSD solicited small missions of opportunity for astrobiology and fundamental space biology under ASTID. The first and only selection made under this program was the Organism/Organics Exposure to Orbital Stresses (O/OREOS) mission managed by NASA Ames. O/OREOS launched to LEO in 2010 and successfully completed its science objectives, yielding many peer-reviewed scientific articles.[1] The mission was developed in under two years and required no new spacecraft bus technology.

SIMPLEx-1

In 2014 PSD solicited for the first time CubeSat missions to conduct planetary science. This solicitation was called the Small Innovative Missions for Planetary Exploration program, also known as SIMPLEx. Proposed missions were cost capped at $5.6M for the full lifecycle of the mission, and were limited to spacecraft with a form factor of 1U, 2U, 3U, or 6U for launch with NASA's Artemis 1 (then known as Exploration Mission 1), which was then expected to occur in July, 2018. Proposals to SIMPLEx were due in April, 2015, with an expected selection in October 2015, leaving a little less than three years for SIMPLEx mission development. SIMPLEx encouraged, but did not require, missions to operate in interplanetary space, expected that the missions would need to advance instrument and/or spacecraft system technology, and were evaluated on the strength of the proposed science as well as the feasibility of the proposed work.

Two missions were selected from this solicitation: The Lunar Polar Hydrogen Mapper (LunaH-Map) and the CubeSat Particle Aggregation and Collision Experiment (Q-Pace). In addition, three proposals were selected for technology development: The Mars Micro Orbiter (MMO) from Mike Malin at Malin Space Systems, the Hydrogen Albedo Lunar Orbiter (HALO) from Michael Collier at NASA Goddard Space Flight Center, and the Diminutive Asteroid Visitor using Ion Drive (DAVID) from Geoffrey Landis at the NASA Glenn Research Center.

The Principal Investigator for LunaH-Map is Craig Hardgrove at Arizona State University. LunaH-Map is a 6U spacecraft carrying two neutron spectrometers designed to orbit the Moon to constrain the quantity of Hydrogen-bearing materials at the lunar South Pole at length scales less than 10 km.[2] New technology being developed for this mission includes a CubeSat-sized neutron detector (Mini-NS), and an electric propulsion system being developed by Busek Co. using solid iodine propellant to provide the 2 km/s of delta-V needed to achieve an elliptical polar orbit around the Moon.[3]

The Principal Investigator for Q-PACE is Josh Colwell at the University of Central Florida. Q-PACE is a 2U spacecraft designed to operate in low Earth orbit carrying a test cell to conduct particle aggregation experiments. The mission's objective is to better understand accretion in protoplanetary disks and planetary ring systems by studying the fundamental properties of particle collisions slower than 10 cm/s in microgravity.[4] Since the mission will operate in LEO, no deep space technology development was required.

Both LunaH-Map and Q-PACE are awaiting launch.

Technology developed by the MMO mission focused principally on a bipropellant propulsion system being developed by Stellar Exploration to provide sufficient delta-V capability to provide Mars orbit insertion. The HALO team built a prototype of optics needed for a 1U energetic neutral atom imager to study lunar hydrogen implantation, and the DAVID team worked to miniaturize a visible-infrared spectrometer to determine the surface color and spectral properties of a small near-Earth asteroid.

Directed CubeSat Missions

As described in the Introduction, the Mars Cube One, or MarCO mission is NASA's first CubeSat mission to deep space. NASA directed its Jet Propulsion Laboratory (JPL) to develop MarCO as a mission dedicated to accompany the Insight mission to Mars. The Insight spacecraft landed on November 26, 2018 and the two 6U spacecraft that comprise MarCO provided a real-time relay of Insight data during its Mars entry, descent, and landing. Each 6U MarCO spacecraft transmitted that data to Earth hours earlier than the Mars Relay Orbiter could, providing early confirmation of mission success. The MarCO CubeSats were launched with Insight and separated early in the transit to Mars, self-propelled by Vacco Industries cold gas thrusters and using a combination of commercial and custom-built subsystems.[5] The attitude control system was purchased from Blue Canyon Technology, the solar array from MMA Design, and the Command and Data Handling and Electrical Power Systems came from Astronautical Development, LLC. The communication subsystems including the high gain reflectarray, medium- and low-gain antennas, amplifiers, and X-band transponder were developed by JPL for MarCO. Because the MarCO spacecraft completed their mission by arriving at precisely the same Mars arrival trajectory as Insight via a primarily ballistic trajectory, the total delta-V needed for the mission was low enough for the use of cold gas thrusters and no propulsion technology development was required.

Partnered CubeSat Missions

NASA is in conversation with the Italian Space Agency (ASI) to launch the Light Italian CubeSat for Imaging of Asteroids (LICIA) as a secondary payload with NASA's Double Asteroid Redirection Test (DART) mission in 2021. LICIA, a 6U CubeSat, would be released from DART close to its arrival at Didymos and would then image the impact ejecta created by DART and relay the data back to Earth. As in the case of MarCO, LICIA would arrive at the same destination as the primary mission and flyby the target destination.

FUTURE SMALLSATS FOR PLANETARY SCIENCE

In 2016 the National Academies of Science published a report about achieving science with CubeSats and concluded that CubeSats had proven their ability to produce high-value science.[6] As described above, SMD had already experienced success with Earth orbiting CubeSats and PSD was ready to advance out into the Solar System using SmallSats.

Concept Studies

PSD released the Planetary Science Deep Space SmallSat Studies (PSDS3) solicitation in August 2016. The objective of the solicitation to was determine what type of planetary science investigations could be done with small spacecraft, what technology development is needed to enable those missions, and what would those missions likely cost? To squarely focus on the first of

Table 1. Planetary Science Deep Space SmallSat Studies

Venus

Valeria Cottini, Cubesat UV Experiment (CUVE)

Attila Komjathy, Venus Airglow Measurements and Orbiter for Seismicity (VAMOS)

Tibor Kremic, Seismic and Atmospheric Exploration of Venus (SAEVe)

Christophe Sotin, Cupid's Arrow

Moon

David Draper, An Innovative Strategy for Exploring the Lunar Surface (IMPEL)

Charles Hibbitts, Lunar Water Assessment, Transportation, and Resource Mission (WATER)

Noah Petro, Mini Lunar Volatiles Mission (MiLUV)

Suzanne Romaine, CubeSat X-ray Telescope (CubeX)

Timothy Stubbs, Bi-sat Observations of the Lunar Atmosphere above Swirls (BOLAS)

Solar System Small Bodies

Benton Clark, CubeSat Asteroid Encounters for Science and Reconnaissance (ROSS)

Tilak Hewagama, Primitive Object Volatile Explorer (PrOVE)

Jeffrey Plescia, Asteroid Probe Experiment (APEX)

Mars

Anthony Colaprete, Aeolus - to study the thermal and wind environment of Mars

Michael Collier, Phobos Regolith Ion Sample Mission (PRISM)

Robert Lillis, Mars Ion and Sputtering Escape Network (MISEN)

David Minton, Chariot to the Moons of Mars

Luca Montabone, Mars Aerosol Tracker (MAT)

Icy Bodies and Outer Planets

Kunio Sayanagi, Small Next-generation Atmospheric Probe (SNAP)

Robert Ebert, JUpiter MagnetosPheric boundary ExploreR (JUMPER)

these questions, proposed mission concepts were required to feasibly cost less than $100M and could make any assumption regarding launch, transportation, and services that might be provided by other, unspecified missions. For the same reason, the mass of the proposed concepts was allowed to exceed that provided by the CubeSat standard, and the limit was set to 180 kg to allow launch using a single ESPA ring port. Over 100 proposals were received, indicating strong interest in the community. Of these, 19 were selected. The titles and principal investigator for each is shown in Table 1, and summaries of each were presented at the 2018 Lunar and Planetary Science Conference.[7]

The selected mission concept studies targeted science spanning the Solar System, including the Moon, Venus, asteroids, comets, Mars, and the outer planets. Although most of these studies started out assuming a CubeSat standard configuration, upon completion only three did (ROSS, Chariot, and CUVE); each of these was a 12U format. The remainder were either small volume probes, or custom spacecraft ranging from 27 kg to exceeding the established 180 kg limit. Several included multiple spacecraft (Ross, IMPEL, BOLAS, Chariot, MISEN, and SAEVe), three included landers (IMPEL, SAEVe, and APEX), and all of them would operate in deep space.

Science payloads for these missions typically included two to three instruments, most frequently imagers in the visible and near infrared. Almost half of the missions would carry spectrometers, including x-ray imaging, thermal emission, UV to IR, time-of-flight, ion trap and

neutron spectrometers. Field sensors were also common, including magnetometers and energetic neutral atom imagers. Lander instruments included seismometers, heat flux and meteorological sensors.

One way to classify these missions is by the amount of delta-V required to accomplish the science. Missions kept delta-V requirements low by two principal means: conducting a fly-by of a near-Earth object, and/or assuming that the primary mission would deliver the SmallSat to its final orbit or flyby destination. Examples of the former include PrOVE and Ross which both targeted objects less than 1 AU from Earth. Examples of the latter include JUMPER, SNAP, SAEVe, Aeolus, CubeX and IMPEL, each of which assumed a rideshare to an initial orbit insertion common with the primary spacecraft. One high delta-V mission concept (Chariot) assumed an initial Mars-headed trajectory from Earth and then achieved the proper science orbit at Phobos and Deimos by using a deployable heat shield for aerocapture. Somewhat similarly, Cupid's Arrow employed a solid rocket motor to achieve Venus orbit insertion after transiting from Earth. The remaining concepts (BOLAS, APEX, CUVE, PRISM, MiLUV, VAMOS, MAT, WATER, and MISEN) are all high delta-V missions that require electric propulsion to achieve the necessary orbit or rendezvous at a distant destination.

Not surprisingly then, the needed technology most often cited by these concept study principal investigators is propulsion systems that can achieve from 1 to 6 km^2/s^2 of delta-V for wet spacecraft masses ranging from 70 to 200 kg and missions ranging from 2 to 6 years. For the missions that did not assume a near-by orbiter to serve as a relay, high data rate communications was also frequently cited as mission enhancing, reducing the need to store large amounts of data on board for later downlink. A data downlink rate of 1 Mbps from locations beyond 1 AU would be useful.

SIMPLEx 2017

Based on the results of the PSDS3 concept studies described above, in 2017 PSD again solicited missions using small spacecraft for planetary science under the SIMPLEx program. This time, in contrast to the ASTID and SIMPLEx-1 solicitations, the cost cap was raised to \$55M and the mass limit was raised to 180 kg. These caps are an order of magnitude higher than those given under SIMPLEx-1, but it should be noted that the cost cap is an order of magnitude less than PSD's Discovery program.

The stated goals of the new SIMPLEx solicitation are to develop and operate targeted science investigations requiring space flight that exploit the unique attributes of small satellites to conduct compelling science, take advantage of available launch capacity to reduce the overall costs of launching multiple missions, provide a means to mature technologies for future missions, and provide additional opportunities to provide flight experience to the community.

The first goal is about the science: every mission is expected to conduct compelling science, addressing questions such as: How did our solar system form and evolve? Is there life beyond Earth? and, What are the hazards to life on Earth? In addition, missions that address the strategic knowledge gaps identified for the human exploration of the Moon are valued. These gaps are understanding the lunar resource potential, understanding the lunar environment and its effects on human life, and understanding how to work and live on the surface. Finally, missions that help to defend the Earth against potentially hazardous asteroids are also of value, where the need is to detect, track, and characterize these asteroids, assess their risk to the Earth, and mitigate against possible hazardous impacts.

The second SIMPLEx goal is to take advantage of available launch capacity to reduce overall costs. In this author's view, the ideal schedule would solicit secondary payloads the day after every SMD mission selection is announced. This would provide typically four to five years to solicit and develop at least one secondary mission (SmallSat) for each launch opportunity to deep space, and would simplify the launch vehicle acquisition process by knowing the mass and characteristics of the both the primary mission and secondary mission(s) before requesting launch vehicle bids. Although this schedule is being discussed, it is not currently NASA policy and may not become so.

The third goal is to provide a means to mature technologies for future missions. SIMPLEx proposals are explicitly not expected to rely solely on technologies having prior flight heritage (although that is ok). The evaluation process permits more technical risk than is customary for larger science missions.

NASA's expectation is that by flying additional, smaller missions with future planetary science missions we will not only increase the amount of compelling science but also involve more people in flight missions, giving them hands-on experience that is invaluable for continued success by the community.

SUMMARY

NASA's Planetary Science Division has embraced the opportunity to develop exciting deep space science missions at a fraction of the cost of traditional missions.

Beginning in 2007, PSD solicited CubeSats for astrobiology studies. O/OREOS, a 6U CubeSat, was launched to LEO in 2010 to study the effects of the microgravity on biological systems. Q-PACE, a 2U CubeSat, is waiting for a LEO launch to study the mechanisms leading to the formation of protoplanetary disks. LunaH-Map, a 6U CubeSat, is being readied for a mission to study the distribution of Hydrogen-bearing materials on the Moon. And MarCO, twin 6U CubeSats, reached Mars in 2018, serving as a data relay system for the Insight mission and demonstrating advanced communication technologies and interplanetary navigation for CubeSats.

These missions have become more capable over the years, and PSD is looking forward to future small spacecraft conducting big science. PSD's goal is to fly small spacecraft as secondary payloads to reduce the cost of missions by taking advantage of available launch mass and volume capacity, mature new technologies, and provide additional flight experience to the community.

References

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