Photon-enabled Planetary Small Spacecraft Missions For Decadal Science

A White Paper

National Academy of Sciences
Planetary Science and Astrobiology
Decadal Survey (2023-2032)

Corresponding Author:
Richard French¹, Rocket Lab
r.french@rocketlabusa.com
(714) 465 5737 x164

Co-Authors: Richard Hunter¹, Mike Loucks², Jonathan Currie¹,
Doug Sinclair³, Ehson Mosleh¹, Peter Beck¹

¹Rocket Lab USA, Inc.

²Space Exploration Engineering

³Sinclair by Rocket Lab (formerly Sinclair Interplanetary)

1. OVERVIEW

Regular, low-cost Decadal-class science missions to planetary destinations enabled by small high- ΔV spacecraft, like the high-energy Photon, support expanding opportunities for scientists and increase the rate of science return. The high-energy Photon can launch on Electron to precisely target escape asymptotes for planetary small spacecraft missions with payload masses up to ~50 kg without the need for a medium or heavy lift launch vehicle. The high-energy Photon can also launch as a secondary payload with even greater payload masses to deep-space science targets.

This paper describes planetary mission concepts connected to science objectives that leverage Rocket Lab's deep space mission approach. The high-energy Photon can access various planetary science targets of interest including the cislunar environment, Small Bodies, Mars, Venus, and the Outer Planets. Additional planetary small spacecraft missions with focused investigations are recommended, including dedicated small spacecraft missions that do not rely on launch as a secondary payload.

Figure 1: The high-energy Photon enables small planetary science missions, including Venus probe missions.

2. HIGH-ENERGY PHOTON

The high-energy Photon (Figure 1) is a self-sufficient small spacecraft capable of long-duration interplanetary cruise. Its power system is conventional, using photovoltaic solar arrays and lithium-polymer secondary batteries. The attitude control system includes star trackers, sun sensors, an inertial measurement unit, three reaction wheels, and a cold-gas reaction control system (RCS). S-band or X-band RF ranging transponders support communications with the Deep Space Network or commercial networks and traditional deep space radiometric navigation methods. A Global Position System (GPS) receiver is used for navigation near Earth. ΔV greater than 4 km/sec is provided by a storable, re-startable bi-propellant propulsion system called Hyper Curie using electric pumps to supply pressurized propellant to a thrust vector-controlled engine. The propellant tanks achieve high propellant mass fraction and can be scaled to meet mission-specific needs.

3. ELECTRON

The high-energy Photon is designed for launch on Electron (Figure 2), Rocket Lab's launch vehicle. Electron can lift up to 200 kg to a 500 km sun-synchronous orbit from either of two active, state-of-the-art launch sites: Launch Complex-1 on the Mahia Peninsula in New Zealand and Launch Complex-2 on Wallops Island, Virginia. As of August 2020, Electron has delivered 53 satellites to orbit building a strong flight heritage with missions for both commercial and government customers including the National Aeronautics and Space Administration (NASA), the Defense Advanced Research Projects Agency, the United States Air Force, and the National Reconnaissance Office.

Electron is a two-stage launch vehicle with a Kick Stage, standing at 18-meter tall with a diameter of 1.2-meter and a lift-off mass of ~13,000 kg. Electron's engine, the 25 kN Rutherford, is fueled by

liquid oxygen and kerosene fed by electric pumps. Rutherford is based on an entirely new propulsion cycle that makes use of brushless direct current electric motors and high-performance lithium polymer batteries to drive impeller pumps. Electron's Stage 1 uses nine Rutherford engines while Stage 2 requires just a single Rutherford vacuum engine. Rutherford is the first oxygen/hydrocarbon engine to use additive manufacturing for all primary components, including the regeneratively cooled thrust chamber, injector pumps, and main propellant valves. All Rutherford engines on Electron are identical, except for a larger expansion ratio nozzle on Stage 2 optimized for performance in near-vacuum conditions.

The high-energy Photon replaces Electron's standard Kick Stage for deep space missions. Photon's flight computer acts as the flight computer for Electron and the RCS used in cruise is also used for Stage 2 roll-control. By removing duplicate subsystems, Electron and the high-energy Photon increase mass to orbit that can be dedicated to more fuel and payload.

4. DEDICATED LAUNCH ON ELECTRON

Rocket Lab's dedicated small launch-enabled deep space missions use the high-energy Photon to target escape asymptotes with progressive phasing orbits to ensure robust, efficient, and accurate departure. Electron first delivers Photon to a circular parking orbit. After separating from Stage 2, Photon performs preprogrammed burns to establish a preliminary elliptical orbit. Photon then performs a series of burns through increasingly elliptical orbits, each time raising the apogee altitude while maintaining a nearly constant perigee. Breaking the departure across multiple maneuvers is an efficient approach to Earth escape. By holding burns close to perigee and limiting their duration, propulsive energy is efficiently spent raising apogee while avoiding the burn losses associated with long duration maneuvers.

Each phasing maneuver is followed by a planned number of phasing orbits at the new apogee altitude. Phasing orbits provide time for on-orbit navigation, maneuver planning, and conjunction screening. Each planned maneuver includes contingency options to mitigate conjunction events or missed maneuvers. After the nominal apogee raising maneuvers are performed, a final injection burn is executed to place Photon on an escape trajectory. Photon can fly integrated with science instruments or with another spacecraft that can be separated to improve staging performance.

All burns are terminated based on velocity using an onboard guidance algorithm that typically achieves better than ~1 m/sec execution accuracy. During ground station passes, GPS data is downlinked to support orbit determination and maneuver reconstruction. The maneuver reconstruction outputs a high accuracy estimate of the Hyper Curie engine performance – a key

Figure 2: Electron has delivered 53 satellites to orbit developing high

input into subsequent phasing maneuvers and, most importantly, the escape burn. By precisely determining the orbit and calibrating Hyper Curie over multiple phasing orbits, Rocket Lab's deep space mission approach ensures that Photon delivers an accurate and precise C₃ at escape, a feature normally reserved for expensive, high-performance upper stages.

The phasing orbit approach also achieves a precise alignment to the required right ascension of the ascending node (RAAN) and Argument of Perigee (AOP) at escape. Photon experiences drift in RAAN while in the phasing orbits due to the Earth's gravitational harmonics. The nominal orbit raising profile, therefore, contains a series of RAAN drift-rate steps associated with each orbit raising segment. The launch time is biased to offset the launch RAAN from the required RAAN by the sum of the RAAN drifts that occur during the phasing orbits. This RAAN-rate profile is planned prior to launch but is adjusted in-flight to compensate for any error in the initial launch RAAN, for missed maneuvers, or other contingencies. Adjustment is achieved by varying the apogee altitude of the intermediate phasing orbits and the number of phasing orbits at each step or by a final RAAN maneuver prior to injection. The phasing maneuvers can also be offset from perigee to actively adjust for any errors in the planned drift in target AOP.

5. SECONDARY GTO LAUNCH

The high-energy Photon can also be carried to orbit as a secondary payload on an EELV Secondary Payload Adapter. By injecting directly into geosynchronous transfer orbit (GTO), the high-energy Photon can access higher-energy trajectories to science targets with increased payload mass.

6. HIGH ENERGY PHOTON PERFORMANCE

Payload mass as a function of C₃ is shown in Figure 3 for dedicated Electron launch of a 320 kg wet mass high-energy Photon and launch as a secondary payload to GTO. For the GTO trajectories, Photon is placed on a 250 x 35,786 km transfer orbit, performs a 200 m/sec maneuver to raise apogee to 110,000 km altitude, and then performs the injection burn. Most missions also require some level of maneuverability for orbit insertion or other purposes post-departure. Post-departure ΔV as a function of departure C₃ for a 25 kg payload on a high-energy Photon is shown in Figure 4.

Figure 3: Photon performance demonstrates usable payload for Decadal-class planetary science.

Figure 4: Significant post-departure Δv is preserved for a representative Decadal-class science payload mass.

7. NASA CAPSTONE

In February 2020, Rocket Lab was selected as the launch service provider for the NASA Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission (Figure 5). CAPSTONE, launching in 2021, is expected to be the first spacecraft to operate in a near rectilinear halo orbit (NRHO) around the Moon. Photon will deliver NASA's 12U technology demonstration CubeSat on a Ballistic Lunar Transfer using the phasing orbit approach described above. The CAPSTONE spacecraft will separate shortly after the escape burn and then demonstrate communications and navigation technology after achieving the NRHO. While NASA performs the primary mission, Rocket Lab plans to execute a secondary mission to demonstrate high-energy Photon deep space operations capabilities with a lunar flyby.

Figure 5: Rocket Lab will demonstrate deep space operations with a lunar flyby in 2021.

8. REPRESENTATIVE MISSION CONCEPTS

Representative mission concepts summarized in Table 1 demonstrate usable payload masses to planetary destinations for both dedicated launch of the high-energy Photon on Electron and as a secondary to GTO. Mission concepts are connected to science objectives to support the *recommendation for more planetary small spacecraft missions with focused investigations using a small number of instruments and dedicated small launch vehicles*.

Table 1: Representative mission concepts support the recommendation for more, small planetary missions.

DESTINATION	MISSION CONCEPT	ELECTRON PAYLOAD MASS (KG)	GTO PAYLOAD MASS (KG)	NOTES
Moon	Low Lunar orbit	29	100	90 degree, 100 km orbit
Moon	Earth-Moon L1	47	156	Goes to L2 first
Moon	Earth-Moon L2	47	157	Direct transfer to L2
Moon	NRHO	37	121	
Moon	Microlander	0.5 to 1.5	5 to 8	Deployed from 90 deg, 100 km orbit
Small Body	Oumuamua Flyby	36	119	Departure: 07 Feb 2017, Arrival: 12 Oct 2017, Relative velocity = 61.7 km/sec
Small Body	Comet Borisov Flyby	12	68	Departure: 09 Jul 2018, Arrival: 25 Oct 2019; Relative velocity = 33.28 km/sec
Small Body	NEO 2000_SG344 - Flyby	43	103	Departure: 15 Apr 2027, Arrival: 20 Jan 2028
Small Body	NEO 2000_SG344 - Orbit	15	66	
Small Body	NEO 2006_BZ147 - Flyby	47	143	Departure 01 Oct 2032, Arrival: 05 Jun 2033
Small Body	NEO 2006_BZ147 - Orbit	12	70	
Small Body	NEO 2018_PM28 - Flyby	38	120	Departure: 01 Jan 2023, Arrival: 15 Jan 2024
Small Body	NEO 2018_PM28 - Orbit	6	55	
Small Body	NEO 2020_OK5 - Flyby	47	142	Departure 14 Dec 2029, Arrival: 03 Oct 2030
Small Body	NEO 2020_OK5 - Orbit	28	98	
Small Body	NEO 2013_WA44 - Flyby	43	137	Departure 18 May 2028, Arrival: 08 Apr 2029
Small Body	NEO 2013_WA44 - Orbit	12	71	
Small Body	Main Belt 1994_SA - Flyby	34	114	Departure: 28 Oct 2024, Arrival: 26 Aug 2025
Small Body	Main Belt 1994_SA - Orbit	-	4	
Small Body	Ceres Flyby	1	113	Departure: 9 May 2029, Arrival: 4 Apr 2031
Mars	Hyperbolic Flyby or Probe	34	115	
Mars	Highly elliptical orbit	10	68	250 km x 34000 km orbit
Mars	Low Martian orbit	-	12	90 degree, 100 km orbit
Mars	Aerostationary	-	28	at about 3 deg
Venus	Hyperbolic Flyby or Probe	33	112	
Venus	Highly elliptical orbit	2	66	200 km x 68000 km orbit
Jupiter	Calisto Flyby	29	104	VEEGA-type trajectory

8.1 CISLUNAR

High-energy Photon missions can enable a range of Decadal-class science at the Moon^{18,51}. Payload masses for representative small orbital mission concepts and a microlander concept are reported in Table 1 (all direct transfers from Earth). Orbiter missions could be used to systematically study the magnetic anomalies³⁸, measure global distribution of ice^{31,36} and volatiles^{25,44,54,55} over extended durations, or perform studies of volatiles before the anticipated wave of human exploration alters

the environment, among others. Low cost penetrator^{31,53} or lander missions could be used to study rocket exhaust plume interactions⁶⁶, help deploy a lunar seismic network⁵², perform in-situ measurements of craters to support solar system chronology^{21,59} studies, perform measurements of lunar swirls at the lunar surface^{12,36}, or visit unique locations like the Aristarchus plateau³⁵ that may not be prioritized on other missions. Communications and navigation infrastructure in support of science and human exploration missions could also be deployed.

8.2 SMALL BODIES

High-energy Photon missions can enable a range of Decadal-class science missions at Small Bodies¹⁶. Payload masses for small flyby and orbital mission concepts to representative targets are reported in Table 1. Photon orbiter missions could investigate small body interior science³² to advance understanding of planetesimal formation²³ and provide a larger sampling of small bodies, particularly main-belt objects or families consistent with ordinary or carbonaceous chondritic compositions⁴¹ and icy⁴⁹ asteroids, to better resolve the diversity of body shapes correlated to surface properties²³. Missions to both Main Belt objects⁴⁷ like Ceres to further study origin, volatiles, and solar system evolution and near-earth objects (NEOs) would support these, other Decadal objectives, and planetary defense^{1,2,7,8,45} needs. Similarly, spectroscopic mission dedicated to measuring isotopic ratios⁴³ could establish correlations with physical or orbital properties of comets. Dedicated missions to perform plasma⁶⁵ measurements could be supported at low cost. Multiple payloads could be launched to take advantage of the Apophis April 2029 encounter¹⁷ to accurately measure the alteration in rotation state and potential internal structural alterations induced by tidal forces¹⁰, supporting both Decadal science objectives and planetary defense. Finally, with adequate warning a responsive mission to fly by an interstellar or Oort cloud object⁴⁸ is possible.

8.3 MARS

High-energy Photon missions can enable a range of Decadal-class science missions^{5, 6} at Mars. Payload masses for small flyby, probe, and orbital missions are reported in Table 1. Orbiter missions⁶⁸ to characterize ionosphere^{9,19} plasma⁵⁷ and magnetic structure, continue studies of igneous rock geology with remote sensing⁶³, improve geodesy⁶¹, determine trace gas flux and variation²⁸, probe the stratigraphy of the upper 10-m subsurface in the mid-latitude ice regions^{13,60}, perform global atmospheric observations⁵⁰ including winds³⁰, or develop atmospheric time series over short⁴⁶, long⁴⁶, and climatological³⁷ scales, could all be supported. Phobos and Deimos¹⁵ could be accessed with focused orbital missions. Payload masses beyond those reported in Table 1 are enabled through small spacecraft aerocapture⁴ capabilities. Lower orbital altitudes are enabled through use of aerobraking. Aging telecommunications infrastructure²⁹ could be more sustainably replenished based on disaggregated commercial small spacecraft capabilities. Technology demonstrations of distributed computing or autonomy²⁴ with small spacecraft at Mars are possible.

8.4 VENUS

High-energy Photon missions can enable a range of Decadal-class science missions at Venus. Payload masses for small flyby, probe, and orbital missions are reported in Table 1. Proposed mission concepts are similar to those identified in the Venus Strategic Plan³⁴ and the Venus

Technology Plan near-term mission modes. Focused investigations of small orbiters with small remote sensing instruments will increase (spatial and temporal) monitoring of the Venus upper atmosphere, such as for airglow⁵⁶ studies, energy and momentum transfer²⁶ in the ionosphere and upper atmosphere²⁰, solar wind interaction, and atmospheric water and other gas loss²⁷; map volcanic activity and surface water transport^{27,58}; perform orbital seismology⁴⁰ or geodesy⁶¹; develop climatological time series³⁷; establish radio science constellations³; or exploit the $\sim 1 \mu\text{m}$ region where the Venus atmosphere is transparent for orbital spectroscopy of the surface³³. Small probes with new thermal protection systems⁶⁴ could deliver Long-Lived In-Situ Solar System Explorer (LLISSE)-based³⁹ seismic stations, instruments to measure the rock types of the Venus tesserae^{27,58,67}, or mineralogy instruments using direct crystallographic techniques¹¹ with a small sampling system. Similarly, small probes can enable skimmer missions or deployment of aerobots²² for in-situ measurements of isotopic ratios⁴³ or to determine the habitability of the cloud layer⁴². Payload masses beyond those reported in Table 1 are enabled through small spacecraft aerocapture⁴ capabilities. Lower orbital altitudes are enabled through use of aerobraking. Low cost communications relays could be deployed with commercial small spacecraft capabilities.

8.5 OUTER PLANETS

High-energy Photon missions can enable a range of Decadal-class science missions at the Outer Planets. The payload mass for a small Jupiter flyby mission is presented in in Table 1. Specific investigations that may fit within this mission approach include visiting Kuiper Belt Object planets, remote sensing of outer planet satellites to study exogenous processes affecting icy satellite surfaces, and a low-cost flyby mission to Calisto, among others.

9. CONCLUSION

The high-energy Photon platform can deliver regular, low-cost Decadal-class science. Representative small mission concepts with Decadal-class science objectives were presented that demonstrate usable payload masses to planetary destinations, particularly for focused investigations. The results support the recommendation for additional planetary small spacecraft missions enabled by dedicated small launch vehicles such as Electron. The results also support balancing the science portfolio to include capability-driven small spacecraft science missions.

10. REFERENCES

1. Abell, Paul. Near-Earth Object Characterization Priorities and Considerations for Planetary Defense.
2. Adamo, Daniel. Toward Greater Preparedness and Resilience in Planetary Defense.
3. Asmar, Sami. Solar System Interiors, Atmospheres, and Surfaces Investigations via Radio Links: Goals for the Next Decade.
4. Austin, Alex. Enabling and Enhancing Science Exploration Across the Solar System: Aerocapture Technology for SmallSat to Flagship Missions.
5. Banfield, Don. Summary of the Mars Science Goals, Objectives, Investigations, and Priorities.
6. Barba, Nathan. High Science Value Return of Small Spacecraft at Mars.
7. Barbee, Brent. Future Spacecraft Missions for Planetary Defense Preparation.
8. Barbee, Brent. Research and Analysis for Planetary Defense In Situ Spacecraft Missions to Near-Earth Objects.
9. Bering, Edgar A. MARSCat: Imaging of the Martian Ionosphere using a CubeSat Constellation.
10. Binzel, Richard. Apophis 2029: Decadal Opportunity for the Science of Planetary Defense.
11. Blake, David. In-Situ Crystallographic Investigations of Solar Systems in the next Decade.
12. Blewett, David. Science Case for a Lander or Rover Mission to a Lunar Magnetic Anomaly and Swirl.
13. Bramson, Ali. Mid-Latitude Ice on Mars: A Science Target for Planetary Climate Histories and an Exploration Target for In Situ Resources.

14. Buratti, Bonnie. The Small Satellite of the Solar System: Priorities for the Decadal Study.
15. Castillo, Julie. Science Motivations for the Future Exploration of Ceres.
16. Castillo, Julie. SmallSats for Small Body Exploration.
17. Cheng, Andrew. APOPHIS 2029 Planetary Defense Mission Options.
18. Cohen, Barbara. Lunar Missions for the Decade 2023-2033.
19. Collinson, Glyn. Exploring the Martian Atmosphere's "dynamo region" to better understand phenomena that impact radio communication at Earth.
20. Collinson, Glyn. Space Physics at Venus: Exploring atmospheric dynamics, escape, and evolution.
21. Costello, Emily. Investigating Impact Processes at all Scales: The Moon as a Laboratory.
22. Cutts, James. Scientific Exploration of Venus with Aerial Platforms.
23. Davidsson, B. J. R. What do small bodies tell us about the formation of the Solar System and the conditions in the early solar nebula?
24. Edwards, Charles. Emerging Capabilities for Mars Exploration.
25. Farrell, William. Lunar polar volatile resources: Obtaining their origin prior to extraction.
26. Fowler, Christopher. Unravelling the drivers of Venusian ionospheric structure, energy balance and evolution, through in-situ plasma measurements at Venus.
27. Frank, Elizabeth. The Thalassa Venus Mission Concept.
28. Garvin, Zachary. Mars Trace Gas Fluxes: Critical Strategies and Implications for the Upcoming Decade.
29. Gladden, Roy. Enabling Robotic and Human Exploration: A Relay Network for the Future of Mars Exploration.
30. Guzewich, Scott. Measuring Mars Atmospheric Winds from Orbit.
31. Hayne, Paul. New Approaches to Lunar Ice Detection and Mapping.
32. Haynes, Mark. Asteroids Inside Out: Radar Tomography.
33. Helbert, Jorn. Importance of Orbital Spectroscopy on Venus.
34. Izenberg, Noam. The Venus Strategic Plan.
35. Jawin, Erica. Exploring end-member volcanism on the Moon at the Aristarchus Plateau.
36. Jhoti, Elisha. An Ultra-Low Altitude Lunar Orbiter.
37. Kleinboehl, Armin. Extended Climatological Observations of Solar System Atmospheres.
38. Kramer, Georgiana. The Plethora of Science Afforded by a Lunar Swirl.
39. Kremic, Tibor. Long-Lived In-Situ Solar System Explorer (LLISSE) Potential Contributions to Solar System Exploration.
40. Krishnamoorthy, Siddharth. Seismology on Venus with infrasound observations from balloon and orbit.
41. Landis, Margaret. Why We Should Study the Themis Asteroid Family in the 2023-2032 Decade.
42. Limaye, Sanjay. Venus, an Astrobiology Target.
43. Lis, Dariusz. Isotopic Ratios in Water and the Origin of Earth's Oceans.
44. Lucey, Paul. Lunar Volatiles Orbiters
45. Mainzer, Amy. The Future of Planetary Defense in the Era of Advanced Surveys.
46. Mayyasi, Majd. How closely-knit is the martian atmosphere system?
47. McAdam, Maggie. Main Belt Asteroid Science in the Decade 2023-2032: Fundamental Science Questions and Recommendations on behalf of the Small Bodies Assessment Group.
48. Meech, Karen. In-Situ Exploration of Objects on Oort Cloud Comet Orbits: OCCs, Manxes and ISOs.
49. Meech, Karen. Main Belt Comets as Clues to the Distribution of Water in the Early Solar System.
50. Montabone, Luca. Observing Mars from Areostationary Orbit: Benefits and Applications.
51. Moriarty, Daniel. The Moon is a Special Place.
52. Nunn, Ceri. MoonShake: a future Lunar Seismic Network Delivered by Penetrators.
53. Paige, David. Small Penetrators for Lunar Polar Science and Exploration.
54. Prem, Parvathy. Lunar Volatiles and Solar System Science.
55. Roth, Nathan. Volatiles in the Next Decade (2023-2032).
56. Royer, Emilie. Importance of airglow and auroral emissions as tracers of Venus upper atmosphere dynamics and evolution.
57. Sanchez Cano, Beatriz. Coordinated multi-spacecraft observations of the Martian plasma environment.
58. Santos, Alison. Venus Petrology: The Need for New Data.
59. Schenk, Paul. The Chronology Problem in the Outer Solar System: Constraining the "WHEN" of Major Dynamical and Geological Events.
60. Siegler, Matthew. Science Case for Microwave Wavelength Measurements.
61. Sori, Michael. Transformative science unlocked by future geodetic data at Mars, Venus, and Ocean Worlds.
62. Thompson, Michelle. Space Weathering Across the Solar Systems: Lessons from the Moon and Outstanding Questions.
63. Udry, Arya. The importance of the study of igneous rocks and compositions to constrain the martian planetary evolution.
64. Venkatapathy, Ethiraj. Sustainability of Mature Entry System and TPS Technologies for Enabling Future Venus Missions.
65. Villarreal, Michaela. The Importance of Plasma and Magnetic Investigations in Small Body Missions.
66. Watkins, Ryan. Understanding and Mitigating Plume Effects During Powered Descents on the Moon and Mars.
67. Whitten, Jennifer. Venus Tesserae: The importance of Venus tesserae and remaining open questions.
68. Zurek, Richard. Mars Next Orbiter Science Analysis Group (NEX-SAG): White Paper Report.