Image of the Earth-Moon system obtained by the Galileo spacecraft on its way to Jupiter December 16, 1992.

Long-Term Commitment to Explore and Sustain Our Earth-Moon Environment

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As individuals intimately involved in US scientific research and space exploration, we wish to share our thoughts and recommendations on the long-term future of space exploration. We represent a broad base of both established and early-career planetary scientists, engineers, and entrepreneurs (at a range of institutions) who are intimately involved with and dedicated to NASA's successful scientific research and exploration undertakings, both human and robotic. From this vantage point we are actively involved in pushing the boundaries of knowledge and discovery as well as training the next generation of scientists and engineers. We seek to do this in a way that is beneficial to humanity and strengthens our nation's technical capabilities in order to ensure that the next generations have a firm foundation upon which to build and grow in the decades ahead.

Findings

Long-term human and robotic exploration of the Earth-Moon environment will move humanity into the Solar System with a logical, sustainable, and science-based approach.

- Focus on the Moon by an expanding international space-faring community presents opportunities for strengthening international cooperation and diplomacy through scientific endeavors.
- The Moon and cislunar space have great potential to stimulate the growing public-private technology sector of our economy, while enabling scientific discovery.
- Science of and on the Moon represents a window into the history of early Earth (and potentially the origin of life) as well as the evolution of small rocky (Earth-like) planetary bodies.
- In the decades ahead, experience gained and investment in the Earth-Moon environment will make the US space program stronger, wiser, and capable of successfully initiating and sustaining human exploration to Mars and beyond, a substantial long-term scientific goal.
- Near-term science and exploration activities in the Earth-Moon system reward the US taxpayer with technical advancements and economic opportunities that benefit life on planet Earth.
- Altogether, a robust, active, sustained and inclusive United States human and robotic space exploration program from the Earth to the Moon and on to Mars and beyond provides invaluable direct and indirect return to US citizens. When this is conducted through a broad international context, it brings enduring benefits to society on planet Earth.

Introduction. Space exploration (with both humans and robots) continues to inspire our nation and the world while simultaneously supporting the economy and strengthening our technology. This century, the world has witnessed an international renaissance in robotic planetary missions to the Moon (and Mars). Since 2000, Europe, Japan, India, China, the US, and Israel have sent missions to Earth's Moon and more are in preparation by Russia, Korea, and new space-faring nations. Perhaps the most far-reaching change in space exploration has been the emergence of a burgeoning private space sector that goes beyond government contracts of the past and has independently developed new capabilities (e.g., reusability of launch systems, human landing systems, etc.). It was especially gratifying to see the successful commercial crew launch and return to the International Space Station (ISS) on the SpaceX Falcon 9 rocket in May/August of 2020. The US space exploration achievements have evolved considerably from the historic accomplishments of Apollo, and space technology is now essential to (and dramatically enhances) life on planet Earth.

As our nation prepares for the decades ahead, we provide thoughts and recommendations on issues that are best addressed with a clear, consistent, and enduring vision. Throughout the discussion below we emphasize several interwoven themes:

- a) It is essential for NASA to retain and continue to lead a *long-term* vision of human and robotic exploration.

- b) An integrated focus on our Earth-Moon environment places emphasis both on addressing immediate climate change issues on Earth (across multiple agencies) as well as reinforcing long-term goals of NASA's human space program. The next steps for the latter begin with the Moon by establishing systems, technology, scientific protocols and investigations, as well as experience essential for sustaining humans on a planetary body that is accessible and close to home, enabling a safe expansion of the horizon to Mars and beyond.
- c) The pervasively international nature of space science and exploration provides unparalleled opportunities for building trust and partnerships with our allies as well as creating new alliances around the world.
- d) Achievable opportunities in the Earth-Moon environment (and the 'cislunar' space between the two) provide stimuli and enable broad economic growth of the commercial space sector into the future (e.g., CLPS, the Commercial Lunar Payload Services program within SMD).
- e) Near real-time breathtaking views of astronauts living and working on the Moon will be awe-inspiring to the nation and the world, especially to young minds, stoking their interest in STEM fields.

Specific topics requiring renewed US leadership in order to reap the intellectual, inspirational, and commercial benefits from the next decade of space exploration are discussed below. We provide groups of **References** as examples and sources of information related to concepts mentioned here.

Long-term Vision and Planning. In polling our colleagues and others involved in space exploration, there is near universal concern that while space science and planetary exploration involves highly technical scientific and engineering activities, it often suffers from a lack of *long-term planning and commitment* that extend beyond political cycles. The health of the US economy, world affairs, and new innovations naturally constrain the *rate and timing* of how individual projects progress, but the primary goals should not radically change with each new administration. To do otherwise is wasteful of both human and fiscal resources and damaging to relationships with our international partners. The strength of the NASA space exploration program comes from providing strong and innovative leadership, systematically accomplishing amazing and inspiring scientific discoveries, and being a consistent and welcoming partner within the expanding space-faring community.

An essential component of national strategic planning is to also strengthen and expand STEM education to achieve a diverse, inclusive, knowledgeable, and highly capable workforce. Exploring the unknown with space science and engineering activities stimulate and enable the next generation of scientists and engineers to engage and prepare to lead (see **Reference R.1** for a few examples and resources). NASA's unique capability to engage and inspire society is derived from intertwined human and robotic missions. These have contributed to and enabled a burgeoning private sector that is initially focused on achievements primarily at the Moon, but also elsewhere in the future. This nascent industry both creates and supports high-end manufacturing and implementation jobs, and its goals inspire students of all backgrounds in STEM. Broad technical aspiration is unprecedented in the history of our nation since the success of Apollo 11 fifty-one years ago.

International Leadership and Participation. While Apollo was an incredibly successful program, it was conducted in a competitive environment of the tense 'cold war' of the 1960's with the then Soviet Union. Apollo landings lasted only until 1972 although Soviet lunar robotic sample return ended later, effectively closing that era in 1976. In contrast, today's environment sees the types of approaches and advances needed to be quite different and must instead be part of a global economic ecosystem. Success increasingly depends on both evolving international cooperation

and also emerging capabilities from the commercial sector. The positive experience demonstrated over the last two decades by the US-led ISS has relied on strong international enthusiasm and support. Commitment continues to evolve with the advent of commercial crew and commercial resupply. Indeed, ISS presents an example of what can be achieved in space through *international cooperation and the longevity such cooperation generates*.

As technology around the world rapidly evolved, more nations have become independently spacefaring, and the Moon becomes their first target beyond Earth orbit. In 2003 ESA (the European Space Agency) launched 'Small Missions for Advanced Research in Technology-1' (SMART-1), which successfully orbited the Moon until 2006. In 2007-2008 first Japan, followed by China, and then India all successfully launched sophisticated spacecraft to orbit the Moon and study it with advanced instruments. In 2009, the US became the last to join this 21st-century group with the Lunar Reconnaissance Orbiter. Additional countries have been significant contributors and participants in these lunar missions and Israel, Russia, South Korea, and others are now preparing new missions to the Moon (see [Reference R.2](#)). China has perhaps been the most active (and successful) recent player with their Chang'e 1-5 missions, including the first successful soft landing on the lunar far side in 2019 with a small rover (Chang'e-4). In addition, China will launch an automated sample-return mission (Chang'e-5) later in 2020, which will mark the first mission of its kind since the Soviets returned the last lunar samples in 1976 (four years after Apollo 17).

Through the right strategic and diplomatic investments, America can lead the world to the Moon and beyond while stimulating a vibrant cislunar economy. We have an unprecedented opportunity to reinforce agreements with our allies and create new and enduring partnerships exploring Earth's neighbor. In today's environment, *to accomplish this long-term goal requires near-term negotiation of viable international protocol agreements for extraction and use of off-planet resources that go beyond the Outer Space Treaty of 1967 and the recent Artemis Accords* ([Reference R.3](#)).

Exploration of Our Earth-Moon Environment. The origin and evolution of the Earth and Moon are intertwined and they have shared the same Solar System environment for the last 4.5 billion years. Much of Earth's geologic history has been erased by active plate tectonics and constant weathering and erosion. In contrast, the Moon's exposed surface and lack of such Earth-like weathering processes passively records and retains an excellent record of cosmic events that have occurred in our part of the Solar System over eons. Earth's atmosphere and magnetic field shield its surface from the constant rain of energetic solar and galactic particles, whereas the exposed lunar surface provides a clean window with which to monitor, record, and study our shared space environment. The Moon is, relatively speaking, nearby and affords an excellent science laboratory to study the history of the Earth-Moon system.

Earth-Moon System: The Earth. Without question, a high priority science-driven task is to provide leadership in recognizing and addressing Earth's rapidly changing climate. It is too late to prevent all consequences (see [Reference R.4](#)), but documenting and understanding the causes and effects, slowing the progression, and mitigating the rate and magnitude of effects, all cry out for decisive leadership and action. Such an enormous task cuts across most federal agencies, including NASA (whose Earth Science Division manages space research with an array of targeted Earth observations), as well as most activities involving interaction with other countries. For example, the IODP collaboration between NASA and NSF (International Ocean Discovery Program, – see discussion in the white paper in [Reference R.5](#)) assessing modern and paleoclimate records (respectively) greatly enhances the values of both data sets and gives insights to the potentially unique situation we face today. We recognize that addressing Earth's climate change is wide ranging and extremely important, but well beyond the scope of this NASA-focused white paper.

Nevertheless, there are aspects of life on Earth that are directly linked with a fundamental commitment by NASA to explore the Earth-Moon environment. Life originated on Earth early in the planet's evolution but, as mentioned above, that ancient history has been erased. However, documentation of the early Earth environment and effects of enormous impact events (basins) that occurred ~4 billion years ago is retained in the impact cratering record of the lunar surface. By sampling and accurately dating the earliest such giant impact basins using current technology, we can reconstruct the early history of the Earth-Moon environment and determine when the surface of the Earth was sufficiently benign to allow life to take hold (*TLS* discussions [Reference R.6](#)).

Discussion continues of possible threat to life on modern Earth from an asteroid or other foreign object hitting our home planet with devastating effects (e.g., Chicxulub, in the Gulf of Mexico – a basin scale impact ~66 million years ago that pushed dinosaurs to extinction –recently explored by IODP). This fear was reignited recently by the meteorite explosion over Chelyabinsk, Russia in 2013 (see [Reference R.7](#)). NASA initiated and still leads a now international observational program to detect and track all near-earth objects (NEOs) that are potential hazards to the Earth-Moon system. This program successfully met a mandated goal of detecting 90% of objects ≥ 1 km (those potentially most dangerous) in 2011, and tracks these large NEOs and now also assesses objects ≥ 140 m and smaller (see [Reference R.8](#)), which are still dangerous, but less of a global hazard.

As we move forward with humans returning to explore the Moon in a sustained way over the next decade, there are enormously valuable benefits that will help meet societal needs on Earth (spin-offs). Envisioned examples include: a) improved and clean power (fuel cells, solar, etc.); b) efficient carbon dioxide scrubbers; c) space-purposed biomedical advances necessary for operating in low gravity that also provide great benefit for common Earth conditions such as osteoporosis. We are still reaping the benefits of miniaturization in size and power needs of everyday electronics that was initiated during the Apollo program (e.g., smart phones) and has evolved into a multi-billion-dollar industry (see [Reference R.9](#) for studies of the economic impact of such programs).

Earth-Moon System: The Moon. The Moon provides an invaluable witness to our past and present as well as accessible opportunities for progressing forward in the decades ahead (e.g., [Reference R.6](#)). In addition to characterizing the impact cratering history of the inner Solar System (see above), the Moon is currently being used to establish the present-day rate of impact events in our planetary neighborhood. NASA has maintained an imaging asset in lunar orbit since 2009, the high-resolution cameras on the Lunar Reconnaissance Orbiter (LRO). By planning and careful targeting of matched repeat images during the last decade the team has documented the formation of ~500 new small impact craters (10s of meters) and the pattern of their extensive surrounding debris across the surface (see [Reference R.10](#)). Such statistics provide direct measurement of the *current* Earth-Moon system impact flux not possible to be measured on Earth due to the atmosphere and oceans. Equally important, these lunar impacts provide important insight into the physics involved for such high velocity impact events on solid planetary surfaces.

The Moon can be used to examine the early history of our Sun. This is enabled through careful targeting and return of lunar soil (regolith) samples developed on the surface between periods of extensive lava flows, which erupted largely between 4.2 and 2.5 billion years ago. Solar components captured as ions in such ancient regolith will constrain the character of the Sun during the period bounded by the sampled ages of lavas above and below the soil horizon.

The planetary-scale size of the Moon also determines its internal evolution (crust, mantle, core), as size is related to the longevity of its internal heat, powered largely by radiometric decay. Since most internal activity ceased much earlier on the Moon than on Earth (which is still active), the

internal structure of the present Moon records an initial stage of terrestrial planet evolution. Studying the interior of the Moon with modern geophysical techniques will permit a glimpse into the early evolution of Earth-like silicate planets.

Tangible Long-term Benefits of Extended Exploration of the Moon:

Expanding the Economy. NASA's current plan of initiating a sustained human presence on the Moon by the end of this decade presents exceptional opportunities for growing a new sector of our economy. By committing to a sustained human presence on the lunar surface, the US will create unprecedented opportunities to private space companies on and around the Moon. These would include areas of logistics (e.g., communications and navigation), re-supply from Earth, use of local resources (e.g., prospecting, resource extraction, refinement for life support and infrastructure materials, rocket fuel, etc.), and perhaps eventually space tourism. As seen from the commercialization of low Earth and geosynchronous orbits, once a culture of private enterprise is established, almost limitless opportunities emerge that fuel economic growth.

In addition to fostering the development of commercial launch services, transportation, and delivery capabilities (SpaceX, etc.), NASA has initiated a program specifically to involve commercial companies in the return to the Moon. The CLPS initiative ([Reference R.11](#)) allows rapid acquisition of lunar delivery services from American companies for payloads that advance capabilities for science, exploration, and commercial development of the Moon. Investigations/demonstrations launched on commercial flights will help the agency study the Moon and open valuable partnerships. In order to ensure that arrays of increasingly sophisticated payloads are available for such flights, NASA has initiated a nested sequence of development programs that allows entry into lunar activities at an early stage ([Reference R.12](#)).

The Human Exploration Laboratory. The Moon is ideally suited for humans learning to live and work successfully off-Earth in a scientifically intriguing, yet close-by, new planetary environment. As experience is gained, this productive and critical progression reduces substantial risks of initiating successful and safe human missions to more distant destinations (i.e., Mars). Equally important, this is achieved while building a vibrant new sector of the space economy at and around the Earth-Moon system. This forward-looking endeavor provides leadership opportunities and inspires and unites the world as humanity expands horizons into the Solar System. The far-reaching scientific discoveries and new engineering challenges found for and on the Moon as this new environment ('8th continent') is explored will motivate the next generation to seriously enter STEM-related careers, as well as spark new technologies that will have direct benefit to society on Earth.

The accessibility of the Moon, situated as it is in the harsh space environment unprotected by the Earth's atmosphere and magnetic field, allows testing of exploration systems that simply cannot be done on Earth or the ISS. The partial gravity environment of the Moon is also an asset. Our two data points, the "1 G" of Earth and essentially "zero G" on the ISS, indicate that the human body is weakened by prolonged exposure to microgravity making human missions to Mars a high-risk endeavor. Developing systems to simulate 1 G conditions for a Mars mission will certainly be costly, but would the negative effects of microgravity be mitigated by one-sixth G, such as found on the Moon? Would creating such conditions for any Mars mission be easier/cheaper? We do not know the answers to these questions, but a sustained human presence on the Moon's surface would allow the options to be addressed. Many other systems are needed to allow humans to survive and thrive off-Earth that can be tested on the Moon to reduce the risks of sending humans farther afield (e.g., engineering landing sites and high-traffic habitat sites, use of local resources, etc.).

Enabling Scientific Discovery and Inspiration. Given continued analyses of returned lunar samples, initial lunar global orbital data that has become available, and the last 10 years of data from the Lunar Reconnaissance Orbiter, it is quite evident that our understanding of the Moon has dramatically evolved since Apollo. For example, we now know there is substantially more water distributed on the surface and in lunar materials than thought from early analyses of Apollo samples ([Reference R.6](#)). Some of this water, existing as ice in permanently shadowed regions, may represent a unique accumulation of Solar System water captured over billions of years. This is not only a scientific treasure, but if found to be in sufficient quantities could have the potential to be a feedstock for life support consumables for human exploration, and as future rocket fuel, stimulating further economic growth. This example highlights where science, exploration, and commercial interests intersect. Unexplored areas of scientific interest have been initially evaluated by available remote sensing data and, together with lunar meteorite samples, demonstrate that our Apollo collection does not represent the full rock-type diversity across the Moon. This limitation significantly hinders our understanding of lunar origin and evolution as well as long-term resource assessment.

There is also much to learn about/from the Moon and its environment. Lava tubes have been mapped in the subsurface and could represent potential locations for human habitation that would be protected from the hazards of meteorite bombardment, solar and cosmic radiation, and the 200°+ temperature swings between lunar night and day. The Moon also affords an opportunity to significantly contribute to Solar System science through measurements that constrain the early, as well as continuing, bombardment history of the inner Solar System, a key condition for the origin (and continuity) of life. Although the protected radio-quiet lunar farside hemisphere is poorly explored compared to the side that always faces Earth, that unique lunar farside advantage can be used to peek into the earliest stages of our Universe through radio astronomy ([Reference R.13](#)).

For the many reasons articulated above, we strongly believe it is both wise and important for the United States and NASA to retain international leadership in space exploration, including a vigorous program of human and robotic exploration and activity with Earth's Moon. From a scientific perspective, the Moon has much to teach us about our home, past and present. From a long-term commercial and resources perspective, the Moon is the unexplored 8th continent. Our accessible Moon is an enabling asset for moving forward in the decades ahead.

REFERENCES with Hyperlinks

R.1 Creating and Maintaining a Strong Next-Generation of Space Scientists and Engineers

It is essential to provide a vibrant next generation of space scientists and engineers through support of STEM outreach activities that encourage young minds, including underrepresented populations, to become the future generations of scientists and engineers. One **example** is a NASA SSERVI team at Georgia Tech partnering with a middle school robotics club. The enthusiastic, young [Freebots](#) won a regional tournament: **Other examples** include:

[ExMASS](#); Harriett Jenkins [postdoc program](#); Minority University Research and Education Project ([MUREP](#))
Next Generation Lunar Scientists and Engineers and Lunar Graduate Student activities: [NextGen1](#), [NextGen2](#), [LunGradCon](#) Next Gen [website](#); LunGradCon [website](#)

An inclusive 'International [Observe the Moon Night](#)' engages the public around the world.

A wide range of continually updated lunar [educational resources](#) are made available to the community through sites such as that maintained by the SSERVI *Center for Lunar Science and Exploration*.

R.2 Example International Lunar Programs

[Europe](#): [India](#): [Japan1](#), [2](#); [Russia1](#); [2](#); [3](#); [Korea](#): [Israel](#); [Canada1](#); [2](#); [China1](#); [2](#); [3](#); International Partnerships: Modern [US-ESA](#): Korea – US [[KPLO](#)]; India-US-ESA [[Chandrayaan-1](#)]: [Overview](#); [M³ Discovers Lunar Water](#):

R.3 1967 Space Treaty and Artemis Accords; + Blog

R.4 Climate Change on Earth

International Climate Change Assessments: *Intergovernmental Panel on Climate Change* [2014](#), [2018](#)

IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the

context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

R.5 NASA-NSF (IODP) Partnerships

R.6 Transformative Lunar Science (TLS) Discussions

SSERVI White Paper: *Transformative Lunar Science* (2018); **NRC/NAS** *Scientific Context for Exploration of the Moon* (2007); See also the Lunar Exploration Analysis Group (**LEAG**) Documents: Lunar Exploration Roadmap (2016); Advancing Science of the Moon report (2018a); Next Steps on the Moon report (2018b)

R.7 Recent Chelyabinsk Meteorite Fall on Earth

Chelyabinsk Meteor: [A Wake-Up Call for Earth](#): Meteor Hits Russia Feb 2013 - [Event Archive](#) Five Years after [Chelyabinsk Meteor](#)

R.8 Asteroids in Earth-Moon Environment: Discovery and Tracking Statistics

R.9 Economic Contributions of Lunar Exploration [Benefits] Examples: A, B, C, D

R.10 The Moon as a Record of Debris Entering Our Earth-Moon Environment

Speyerer E. J., et al (2016) [Nature](#); Speyerer E. J. et al. 2020, *LPSC #2369*

At the beginning of 2020, after a decade of operation, LRO has documented formation of a total of ~500 small new craters from matched temporal pairs over 20% of the lunar surface. Dated and exquisitely preserved [new impact craters](#) resulting from debris in the Earth-Moon system also reveal physical effects of such high velocity impacts on rocky bodies in unprecedented detail.

R.11 Commercial Lunar Payload Services (CLPS)

NASA's CLPS initiative allows rapid acquisition of lunar delivery services from American companies for payloads that advance capabilities for science, exploration or commercial development of the Moon. Investigations and demonstrations launched on commercial Moon flights will study Earth's nearest neighbor: [Overview](#), [Initial companies](#)

R.12 Active NASA Instrument/Technology Development Programs

A pathway for advanced instrumentation to be developed and flown is key for maintaining cutting edge capabilities and engaging the next generation in science and exploration projects. Some productive example programs that encourage broad participation and lead to operational flight systems include:

[PICASSO](#) (Planetary Instrument Concepts for the Advancement of Solar System Observations) - supports the development of spacecraft-based instrument systems that can address specific scientific objectives of future planetary science missions to any Solar System body except the Earth or Sun. Funds the development of new proof-of-concept instruments and is aimed at low Technology Readiness Levels (TRL 1-3) so that successful instrument concepts can later be proposed to DALI or MATISSE.

[MATISSE](#) (Maturation of Instruments for Solar System Exploration) - supports the advanced development of spacecraft-based instruments that can be used on future planetary science missions. Supports developing instruments from TRL 4 to TRL 6 so that they can be proposed to future announcements of flight opportunity (e.g., LSITP).

[DALI](#) - Development and Advancement of Lunar Instrumentation - Funds spacecraft-based instruments so that they can be further matured and ready for use in future lunar lander missions. The goal is to develop lunar science instruments so that they are ready to be proposed to future announcements of flight opportunity without extensive additional development. Advances instruments to Technology Readiness Level 6.

[LSITP](#) (Lunar Surface Instrument and Technology Payloads) - funds flight payloads to be ready quickly and that do not require additional significant development. These payloads will fly on near-term Commercial Lunar Payload Systems (CLPS) missions.

[PRISM](#) (Payloads and Research Investigations on the Surface of the Moon) – an open solicitation for additional potential payloads to be delivered to the lunar surface through the agency's Commercial Lunar Payload Services ([CLPS](#)) initiative.

[LuSTR](#) (Lunar Surface Technology Research), example current NASA solicitation. The goal of LuSTR is to accelerate the development of groundbreaking technologies that support and enable lunar surface activities. LuSTR solicits proposals that relate to two Innovation areas: In-Situ Resource Utilization and Sustainable Power.

R.13 Radio Astronomy from the Farside of the Moon

Burns, Jack O. (2020) Observations of the Dark Ages ... at Low Radio Frequencies, [Phil. Trans. R. Soc. A](#). Bassett, N., D. Rapetti, J.O. Burns, K. Tauscher, R. MacDowall, (2020) [Advances in Space Research](#).