ASCEND

ENSURING ECONOMICALLY VIABLE LUNAR SETTLEMENTS

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STATEMENT OF ATTRIBUTION

This report is the outcome of the ASCENDxCo-Lab on Economically Viable Lunar Settlement held on 29 July 2020. It was drafted, reviewed, and approved for release by the AIAA Public Policy Committee in September 2020. More than 200 space industry leaders and experts participated in the virtual workshop, representing academic institutions, commercial enterprises, government agencies, and professional societies from around the world. This report reflects the collective views of the workshop participants and is not necessarily a position of AIAA at large.

EXECUTIVE SUMMARY

Return to the lunar surface is the next great step for human space exploration. Lunar and cislunar space present enormous opportunities for scientific exploration, economic growth, and long-term off-world human settlement, as well as a gateway to Mars and beyond. In April 2020, NASA released *NASA's Plan for Sustained Lunar Exploration and Development* [1]. This plan outlines NASA's three-domain exploration strategy – to return humans to the lunar surface in 2024, to lay the foundations of a sustained long-term presence on the moon, and to pave the way for crewed Mars exploration – placing the Artemis program at the core of NASA's human spaceflight and exploration strategy for the next decade. While NASA's plan identifies the foundational capabilities required, including habitation modules, surface mobility units, and an increased robotic presence, there are numerous technological gaps and economic considerations that must be addressed to realize the dream of a truly self-sustaining and economically viable lunar settlement.

In July 2020, as part of a series of events leading up to the inaugural ASCEND event, the American Institute of Aeronautics and Astronautics (AIAA) conducted the *ASCENDxCo-Lab on Economically Viable Lunar Settlement*, a collaborative workshop convened to discuss and respond to NASA's plan [2]. This report presents a summary of the findings of the workshop, examining the technological and economic conditions that need to be established to move towards a sustained and economically viable lunar presence, as well as the role of national space agencies, governments, and industry in addressing these conditions. For this analysis, a *sustained* lunar settlement is defined as one that meets the test of continuous survival and operation over time, and an *economically viable* settlement is defined as one for which the long-term cost of the continuous investment in its maintenance is ultimately underwritten by private capital. This report was prepared by the authors but represents the combined inputs of more than 200 attendees.

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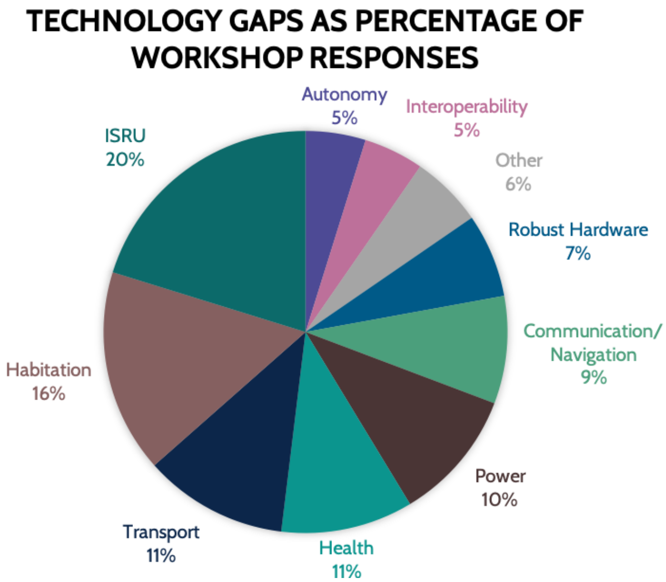
TECHNOLOGY GAPS

NASA and its international partner agencies have spent the past 20 years successfully proving technologies to enable astronauts to live for months in low Earth orbit (LEO) aboard the International Space Station (ISS). However, shifting from temporary habitation of an orbiting laboratory to long-term lunar settlement requires the fielding of a variety of technology areas, many of which are currently at a low Technology Readiness Level (TRL). Workshop participants identified the following technologies as crucial for enabling an economically viable lunar settlement. Increasing TRL in these areas will ensure the settlement is not entirely reliant on Earth for resources, power, and capability, as well as providing potential business opportunities for commercial entities.

- In-Situ Resource Utilization (ISRU) – ISRU is one of the most frequently cited technology gaps when considering long-term space exploration and settlement. The goal of achieving economic viability on the moon is only possible if the capability exists to detect, extract, process, and utilize lunar resources. Large-scale resource mining for lunar regolith, water, and volatiles must be developed that can operate autonomously (or semi-autonomously) and in the harsh lunar environment. Autonomous processing and additive manufacturing capabilities will allow these resources to be utilized to build infrastructure and hardware components, life support, and agricultural systems, as well as fuel for surface and launch/landing transport systems. With such an unproven technology, it is vital that ISRU be a core component of NASA's critical path to lunar settlement.
- Long-Term Habitation Systems – To enable a truly Earth-independent lunar settlement, habitation systems that do not rely on resupply from Earth for food and life support will need to be developed. This includes technologies for closed-loop or regenerative life support systems, crop growth and harvesting, water and waste processing and recycling, and improved radiation shielding. Habitats and infrastructure designed for lunar settlement should aim to be easily deployed, either through self-assembly or remote assembly via autonomous or telerobotic systems. Artificial intelligence provides a possible avenue for the management and maintenance of these habitats.
- Surface and Lunar Transportation Systems – Earth to cislunar, cislunar to lunar surface, and surface transportation systems will form a key component of any long-term lunar settlement. Reliable and low-cost Earth-moon transport and supporting infrastructure (launch and landing pads, refueling depots, etc.) are crucial to support Earth-moon-Mars supply chains and the transport of lunar residents. It is vital to raise TRL for low-cost reusable descent and ascent vehicles for the lunar environment, regolith stabilization to support multiple landings and launches, and alternative propulsion methods such as nuclear or electric propulsion.
- Human Health – The maximum time an astronaut has spent in a microgravity environment is 438 days. For lunar and Mars missions improved mitigation strategies for the known effects of microgravity should be investigated, and further investigation into the long-term effects of microgravity environments will be needed.
- Power Generation and Distribution – Currently the largest power generation in orbit, the 1 acre of solar panels aboard the ISS is capable of generating 84-120 kW. For comparison, McMurdo Station in Antarctica requires approximately 2-3 MW to operate heating and laboratories for ~1200 residents. A comparable lunar settlement is likely to have power requirements several orders of magnitude beyond current orbital capabilities, particularly with the addition of mining and transport equipment. Large-scale power generation via nuclear or solar power must be developed that can cope with the temperature extremes of the lunar day-night cycle, as well as support habitation, exploration, ISRU, and scientific research. Efficient and lightweight methods of power transmission, such as power beaming, and power storage and portability, are critical technologies that must be developed to enable large-scale, distributed lunar settlement and surface transport.



- Communication and Navigation Systems – While telecommunications and GNSS-reliant navigation systems are ubiquitous on Earth, no such capability yet exists on the lunar surface. A long-term lunar settlement will need a reliable, large-scale Position, Navigation, Timing, and Communications (PNTC) network to provide capabilities such as absolute positioning to within 1 meter to support surface exploration and transport, and communications analogous to cellular and internet services on Earth. Communications systems will need to support high-bandwidth transmissions to enable telerobotic operation of assets, video links, and timely transmission of data to Earth.
- Robust and Reliable Hardware – The lunar surface is a harsh environment, and thus any lunar hardware will need to be highly robust and reliable, radiation-hardened, and designed to operate across the wide temperature range (4-400 Kelvin) of lunar day-night cycles or at the extreme low temperatures within permanently shadowed regions. Additionally, significant investment in lunar dust mitigation technologies is key, both for hardware and human survivability. Lunar regolith simulants of better quality and higher quantity will need to be developed to qualify flight systems for lunar operation. Additionally, given the long-term nature of a settlement, hardware should be designed for increased life spans, and/or the ability to be easily upgraded over time.
- Interoperability and Standardization – A key technology gap moving forward with long-term lunar plans is developing interoperable space systems. Working with international partners and working across public and private sectors, technology interfaces and architectures will need to be standardized and have systems of systems that are compatible and able to exchange information.
- Autonomous Systems and Telerobotics – Raising the TRL of autonomous systems and increasing the use of artificial intelligence in space systems will help to address some of the above technology gaps. A long-term settlement will likely rely on autonomous fault detection and maintenance systems to lessen the burden of work on human residents. In addition, highly autonomous robotic systems can aid in exploration, ISRU, and remote sensing.

The NASA plan makes it clear that the path for future lunar exploration has the ultimate goal of a long-term sustained presence; however, this will only occur "once [technologies and capabilities] of the moon to Mars campaign are delivered and operational [3]." Designing solely towards the goal of a 2024 lunar landing and a Mars landing in the 2030s, with little consideration for long-term lunar presence, could result in innovative but short-lived and small-scale technologies that do not effectively support a sustainable lunar settlement. When developing the technologies outlined in the plan – such as surface transport or habitats – durability, upgradeability, and scalability of these technologies need to be considered. For example, when evaluating concepts for a foundational surface habitat, designs should be selected that address the technology gap of *interoperability and standardization*, thus enabling future construction to be built upon existing infrastructure as more players arrive on the lunar surface. Long-term planning is required to ensure that each technology developed addresses the gaps outlined above and, ultimately, supports long-term settlement.

As noted in "The Role of NASA and its International Partner Agencies" section below, public sector funding and investment will be critical to filling these technology gaps. The award of long-term "anchor tenant" contracts is one way governments can provide the market certainty needed by industry to invest in these technology gaps.

ECONOMIC CONDITIONS CONDUCIVE TO SUSTAINED LUNAR SETTLEMENTS

The findings of this workshop highlight that the vision for a sustained lunar settlement is the emergence of a diverse space economic ecosystem over the long term. The development of commerce and industry in space is a key component of any long-term lunar settlement and the long-term economic success of such a settlement relies on several key economic conditions:

- Role of Government - *NASA's Plan for Sustained Lunar Exploration and Development* and the findings of this workshop both highlight that there is an inherent role for the government in advancing lunar economic development. Governments can nurture the emergence of baseline physical, social, and legal infrastructure that will serve as a scaffold for private entrepreneurial activity in space. Government entities should support the development of commerce and industry in space through investment in space infrastructure, support for research and technology development, and promoting a secure and predictable environment in space. Among nations with space programs, those with strong economies are seen as most likely to support such investment and as the key early strategic partners for international collaboration, burden-sharing, and rule-setting. A thriving space economy will emerge only if space is open to free enterprise. Government, as the first but not the only customer, can steer technology development, buy down risk, and stimulate private investment in key capabilities in transportation, logistics, communications, energy, and habitation. In addition, the role of government should be carefully defined so as not to position the government to compete with private industry.
- Motivation – The establishment of any space settlement will rely on a key driver or socioeconomic motivation. Possible drivers include a fairly prosperous Earth economy; a response to an ecological catastrophe or scarcity of key terrestrial resources; a push to secure new resources and/or create new markets for Earth; or the urge to explore. Longer term, an established settlement is motivated to self-sustain a viable and growing population.
- Needs Analysis – The diversity of needs of various stakeholders must be considered. Governments need strategic advantage in the event of rivalry; scientists and space agencies need unique knowledge that is only found in space; investors and corporations need predictability of and respect for property rights and returns; markets need a space economy that generates net real wealth; and the public needs to have a clear idea of the motivation for a lunar settlement.
- Transportation and Logistics – To support a thriving lunar economy and future supply chains, Earth-moon transport needs to be more accessible. To this end, a critical economic condition is the order(s) of magnitude reduction in launch costs without compromising safety. Falling costs, a strong focus on safety, and increasing capacity are currently on track with programs for the commercial transportation of humans to LEO and of cargo to the moon. Over the medium to long term, lunar propellant resupply from ISRU and safe, reliable habitation at the destinations will continue driving costs down and capacities up.

- Investment – Public investment would be motivated by national interest, economic development, and public support, whereas private investment would be motivated by legal and institutional certainty, knowable risks, and the expectation of profits. For business cases to close, governments must establish institutional credibility and buy down risk for commerce, including protection of private property rights; the cost of access to space must fall; publicly funded infrastructure must be in place; and, optionally, government can be the first but not the only customer for space products and services. It is likely that potential profits within a <10-year venture capital time horizon will attract increased investment capital, further justifying the public buy-down of risk.
- Habitation – Long-term space settlements are both socioeconomic and physical constructs, and thus are subject to complex dynamics that are not familiar to space programs. To support a thriving economy, settlements need to be safe, comfortable, and interesting so as to attract potential residents and workers. Long-term investment in human-centered settlements with sophisticated socio-technical designs will support a positive feedback loop between happiness and productivity, which are conducive to economic viability.
- Resource Extraction – The costs associated with the extraction and processing of water, volatiles, and minerals on the lunar surface currently make it difficult to justify as a standalone business case. Governments should focus on investment in large-scale mining of water ice and regolith, thereby reducing transport costs through fuel and launch/landing infrastructure, with facilities transitioning to the private sector when the business case becomes viable. Robotic mining, which is now available on Earth, may be part of business cases for mining on the moon. Additionally, regulatory frameworks regarding ISRU must be established to provide private entities with clear guidelines on resource ownership and use.
- Industrial Development – ISRU, transportation infrastructure, habitat construction, and tourism are likely to be synergistic industries that would benefit from simultaneous development. Humans on-site add value to industrial processes, while robotics, telerobotics, and artificial intelligence could augment scarce labor, reduce risks and ensure safety for tourists. Efficient manufacturing for space and for Earth would require orders of magnitude reductions in transport costs, an ISRU-based value chain, and re-use or adaptation of commercial off-the-shelf (COTS) technologies, where possible. There are first mover advantages with respect to locations that can support long-term organic growth.
- Products, Services and Other Outcomes – Once the preceding economic conditions are met, free markets will discover product and service opportunities, possibly among the listed technology gaps. As we cannot yet predict what these will be, infrastructure planning should allow, support, and encourage markets to experiment with a diverse variety of "people" and "value-adding" activities. Some examples included exploration data, resource mapping, lunar science infeasible from Earth, tourism, products valued on the moon and on Earth, and leasing of habitable space to a variety of users. In the long term, and with critical mass, more ambitious business cases might close, such as support for mega-engineering projects in cislunar space, lunar sport and entertainment, and permanent lunar settlement.
- Sustainability and Other Conditions – A key condition for long-term sustainability is that all supporting infrastructure for humans and robots will have to be maintained. For this to happen, stakeholders must have the economic motivation to do so. Thus, in the short and medium term, the settlement must provide value back to the public or private Earth sponsors. In the longer term, the settlement must be on a path of ever-increasing economic independence, aspiring towards a self-feeding economy characterized by organic growth and supported at most by small, flat public funding. Further factors to promote sustainability are a stewardship mindset, generational learning, reducing wealth gaps and engaging populations, and channeling the human instinct to explore towards peaceful outcomes.

INFORMATION NEEDED TO ADVANCE TECHNOLOGY AND ECONOMIC CONDITIONS

A thriving economy, including the conditions listed above, is predicated on good information flow. In order to advance sustainable, long-term economic conditions on the moon and address current technology gaps, stakeholders need access to reliable and accessible information, to understand where there is potential for technology development or business opportunity, as well as policy issues regarding consensus rules of engagement for all actors. There are several key information areas that require greater data collection or definition:

- Understanding Availability, Mining, and Applications of Lunar Resources – Development of ISRU technology is useless without knowledge about the types of resources on the moon and their distribution, as well as how to work with the materials and their applications. There is an opportunity for lunar missions to focus on lunar materials and products that may be in short supply on Earth in the future, or cannot be produced easily elsewhere, which could have a strong return on investment.
- Market Development and Customer Discovery – A key aspect of establishing a lunar economy is discovering viable markets and customers. Supply and demand need to be aligned, as well as a determination of the cost of products and services, and an understanding of potential profit and customer needs. Revealing what customers want will be a difficult task, but it is vital to a lunar economy. Market development and customer discovery could be conducted by a commercial partner with expertise, as was the case with NASA's LEO commercialization plan [4].
- Innovative Business Cases – Business cases for the moon remain a major open question. Workshop attendees believe that there will need to be incentives for businesses to go to the moon. Businesses could start by identifying low-hanging fruit in business ideas, but they must also plan for the long term. New figures of merit will need to be developed to assess the strength of proposed business plans. Although this is a difficult challenge, we can leverage the management lessons learned from New Space companies that are advancing the state of the art.
- Consensus Rules of Engagement – NASA's Artemis Accords are a good start to consensus rules of engagement, and more work will need to be done to ensure safe exploration of the moon [5]. With governments around the world and commercial partners planning to go to the moon, consensus will need to be built on numerous topics, including intellectual property, property rights, collaborative environments, resource sharing, and standards, to name a few.
- Marketing – The space community needs to improve its marketing, both to companies and to the public. Companies that have not previously been involved with space exploration should be tapped and small businesses should be encouraged. Space explorers need to shift the public perspective of space toward understanding its potential to solve the most pressing issues of humanity's future, including growing energy needs. Space needs to benefit not just the wealthy and the privileged, but everyone on Earth –and this will only be achieved when we tap into the full spectrum of talent, including groups that have typically not been involved.
- Technology Development and Scientific Research – The technology gaps listed previously require significant scientific information gathering. These areas include, but are not limited to, greater knowledge of long-term effects of microgravity on the body, food production in micro- or low-gravity environments, life support systems, effects of long-term isolation on human behavior, solar power distribution, performance of hardware and materials at extremely low temperatures, and developing manufacturing processes for micro- and low gravity. This needs to be supported by significant investment in scientific research. In preparing the National Academies' next decadal survey on Life and Physical Sciences Research in Space, the alignment of proposed areas of research with the goals of a long-term lunar settlement could be considered as an additional figure of merit when assessing what research to make the national priority [6].

- Strategic Planning – NASA and international partners need to continue strong strategic planning for lunar exploration, including technology roadmaps such as the 2020 NASA Technology Taxonomy to carefully articulate and map capability needs, design reference architectures, and detailed plans for core technologies like communication and power distribution [7].
- Delineation of Relationships – It is vital for the relationships of all lunar actors (including government, commercial, and international partners) to be defined. These delineations should include plans for commercialization, sustained levels of funding, and further development of relationships with international partners.

THE ROLE OF NASA AND ITS INTERNATIONAL PARTNER AGENCIES

In moving from initial landing and exploration to a sustained lunar settlement, the role of NASA and its partner agencies must shift. The current model for government-industry partnerships, with the government acting as a customer to acquire needed capabilities, cannot be sustained long term. As NASA refocuses on its long-term exploration efforts for Mars after establishing lunar operations, private industry must take up new roles to deliver increased capability at lower costs; however, as highlighted above, there are major challenges for private industry to develop viable business cases for lunar-based operations at present. These include the significant investment required to gather information about lunar resources, a lack of customers or target market, and no clear national and international legal framework within which to operate. Consequently, in addition to their role in establishing early economic conditions for a lunar settlement and acting as an inaugural customer, NASA and its partner agencies should focus on the following steps to pave the way for private industry investment:

- Geological and Environmental Information – Companies face significant information gaps when considering business cases for lunar development. NASA and other government agencies should position themselves to generate and make publicly available data that can reduce the burden of risk for businesses looking to operate on the moon. A key information area already highlighted is that of lunar resources. As ISRU emerges as a key area of interest for commercial development on the lunar surface, significant capital investments are required for initial surveying operations. Rather than placing the burden on a single corporate entity, NASA should organize an effort to gather widespread and comprehensive geological and environmental information for the lunar surface. As well as providing knowledge about the availability of local resources, this information will inform the development of equipment and hardware. This will help companies select sites for further, privately-funded study and development.
- Regulatory and Legal Standards – NASA should encourage the prompt development of clear regulatory and legal standards for companies working on the moon, including robust engineering standards for hardware and issues surrounding property rights. Efforts should also be made to ensure the protection of space businesses' intellectual property, while still encouraging information sharing in this early stage of economic development. Existing legal frameworks for operating in non-sovereign environments – such as in the Arctic and Antarctic – can be used to advise both national laws and international agreements to facilitate this process.
- Public Sector Funding and Investment – Government contracts are going to remain a key source of revenue for lunar companies for the foreseeable future. NASA and other space agencies should provide long-term direction for the usage of the moon, along with long-term contracts for the private sector beyond just launches and landings. This could take the form of large-scale scientific projects, such as a lunar telescope, or a government-funded survey effort that contracts with private entities. In the future, additional government agencies can take over some of these responsibilities, with the United States Geological Survey or a similar entity taking over the role for collating survey data, for example
- Education and Outreach – Lunar companies require a trained and motivated workforce in order to develop the innovative business strategies and technologies required for lunar settlement. NASA is preeminently placed to support and encourage the professionals of the future in both STEM and other relevant fields. NASA's Office of STEM Engagement and other outreach efforts should be viewed as investments in developing the skills needed for both the public and private lunar sectors and funded accordingly. Given the large amount of scientific and technical knowledge needed to address key technology gaps, NASA should also continue to invest heavily in academic and research grants.

ENGAGEMENT OF NON-AEROSPACE INDUSTRY AND GOVERNMENT PARTNERS

Government-industry partnerships have always been at the core of the United States space program and will be essential for building a sustained lunar settlement. However, given the diversity of expertise and capability that will be required for a long-term lunar settlement, these partnerships must become multidimensional, and industries outside of the traditional aerospace partners should be engaged. Additionally, *NASA's Plan for Sustained Lunar Exploration and Development* highlighted that the success of a sustained and vibrant lunar settlement would require not only the participation of NASA's commercial partners and international partner agencies, but also that of the wider U.S. government. It is crucial to identify key industry partners and government agencies outside of NASA that should be consulted, to address information gaps and ensure long-term economic viability, as well as decrease development times for any required technology. Three examples of non-traditional industry engagement have been highlighted below to show the potential for addressing key technology gaps. A follow-on table gives a comprehensive list of potential non-space industry actors to engage for long-term lunar settlement. While 'short term' and 'long term' were not explicitly defined during the workshop, for the purposes of this paper we are defining short term as the next 10 years, and long term as the next 50 years.

- Healthcare, Agriculture, and Food Processing – The health and well-being of lunar residents will be a crucial contributing factor to the success of a long-term settlement. Healthcare professionals such as doctors, nurses, physical therapists, and those who deal with emergency environments, such as emergency medical technicians, will provide great insight on emergency preparedness and the overall health of the astronauts. In addition to healthcare, astronauts will need other essentials such as food, water, and air. Consultation with the agricultural industry will be crucial for achieving successful crop harvesting on the moon, and thus ensuring less reliance on food being shipped from Earth. Other food-related industries such as food safety, packaging, and manufacturing should also be consulted. Expertise from water and waste management industries may provide insight for recycling and cleaning water and waste, and thus for the sustainability and sanitation of the settlement.
- Utilities – Power and communications, are critical utilities required for a long-term, safe lunar settlement. Insights into power collection could come from the solar or nuclear energy industries, both promising areas for energy harvesting. Power distribution in space on the scale of a large lunar settlement has never before been attempted, so engagement with power distribution companies will be vital. Likewise, communication networks on this scale will benefit from the expertise of existing telecommunications companies.
- Mining and Construction – As has been previously stated, ISRU is a key technology for sustained lunar settlement. The mining industry on Earth has a wealth of knowledge to provide in the areas of autonomous and safe resource extraction and processing. Given the hazardous, high-risk environment of the lunar surface, expertise from similarly hazardous industries here on Earth, such as off-shore and ice-drilling companies, may provide useful insight into remote operations in hostile environments, safety regulations, and hardware needs. Since much of the lunar resources mined from the surface will be utilized on-site for landing pads and building infrastructure, best practices of the Earth construction and excavation industry should be utilized for safe and efficient construction on the moon.

	Industry	Possible Applications for Lunar Settlement
SHORT TERM (next 10 years)	Healthcare	Astronaut life support, microgravity research, emergency and onsite care, mental health
	Food/Agriculture	Regenerative life support systems, lunar farming, design of closed-loop habitats, food storage
	Waste Management	Organic and non-organic waste recycling, closed-loop life support
	Water Management	Lunar farming and irrigation, life support, water recycling for humans
	Construction	Utilization of regolith, construction of buildings, landing pads
	Mining	In-situ resource utilization, telerobotics
	Manufacturing	In-situ resource utilization, self-assembling habitats, microgravity manufacturing
	Energy	Lunar power grid development, storage and portability of power for surface transport and distributed lunar settlements, power transmission
	Automotive	Manufacturing and mass production, human surface transport, robotic exploration
	Aviation	Space traffic control and management of Earth-moon transport network; development of safe, reliable, comfortable, low-cost human space transport
	Marketing	Garnering public support for lunar exploration, communication, and information flow
	Education	Research in technology and information gap areas, training lunar workforce
	Telecommunications	Establishment of lunar cellular/internet services, navigation systems
LONG TERM (next 50 years)	Management	Earth-moon supply chain management, lunar settlement management, logistical support
	Urban Planning	Large-scale lunar settlement planning, roads, community management
	Architecture	Habitat design including community spaces, personal quarters, accommodation
	Insurance	Health insurance, accident protection
	Finance	Banking, public funding, venture capital
	Policy	Local governance, international policies, conflict resolution, protecting property rights
	Tourism	Space tourism, hotel design and management, activity planning
	Entertainment	Lunar/microgravity sports, filmmaking, music

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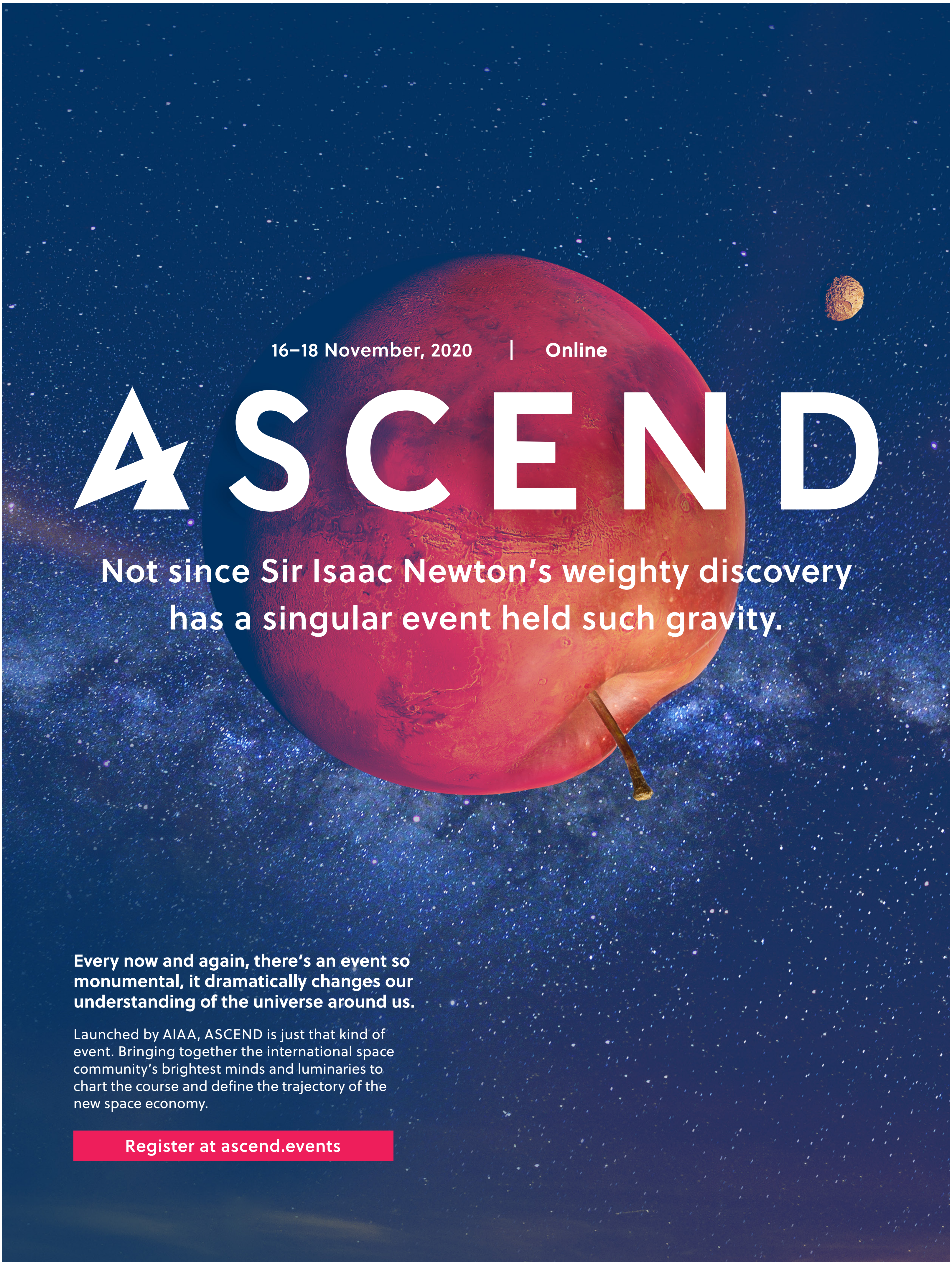
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