What would it take to manufacture perovskite solar cells in space?

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Imagine, astronauts land on the moon. They verify their arrival with mission control, and perform system checks and validations. After the dust settles, they open the airlock of the landing vehicle and venture outside. A side hatch opens, and a flexible substrate slowly unfurls on a boom. A series of printer heads raster, hovering over the substrate and sequentially vapor-depositing the constituent layers of a perovskite solar module (Figure 1). In time, a 1-megawatt array has been manufactured on the moon and can now be connected to supply power to the Artemis Base Camp. This ambitious vision could someday become a reality. On August 29, 2021, a SpaceX Falcon 9 rocket launched a commercial resupply payload from Kennedy Space Center *en route* to the International Space Station (ISS). On board were perovskite solar cells that will fly for 6 months outside the ISS in low earth orbit (LEO) on the 15th Materials International Space Station Experiment (MISSE-15). This will be the first long duration flight of perovskite solar cell devices in LEO and a major step toward realizing the in-space operation and, potentially, manufacture of perovskite solar cells.

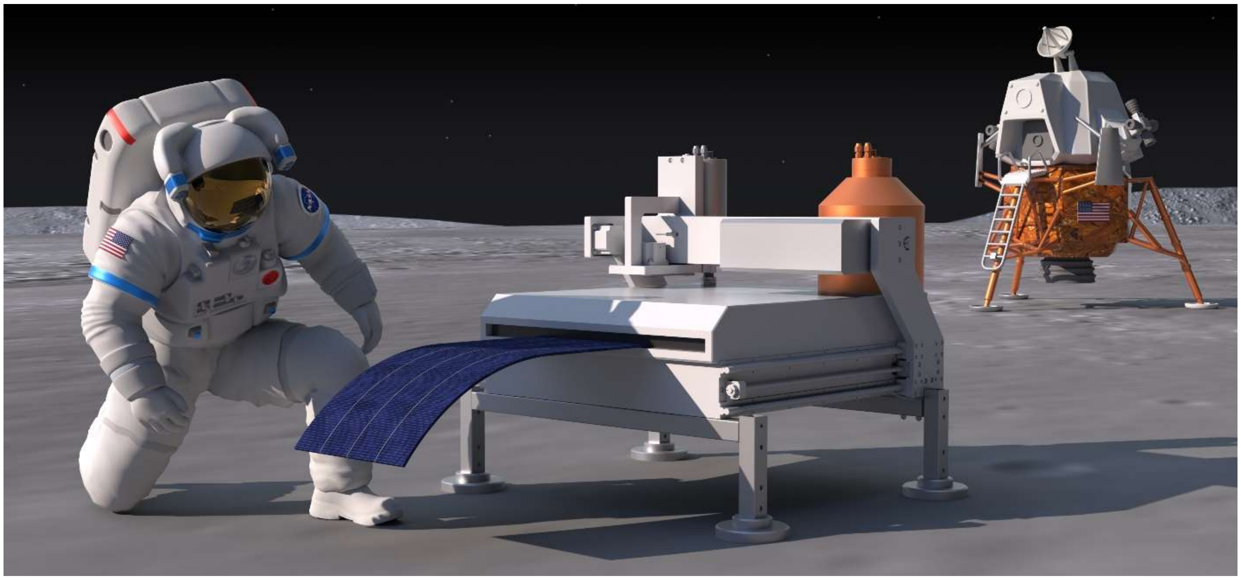

Figure. Artist rendering of lunar lander vehicle with sequential in-space printing of perovskite solar module.

Metal halide perovskites' excellent optoelectronic characteristics and facile manufacturability have made them attractive candidates for photovoltaics. These traits coupled with their radiation tolerance and defect tolerance have garnered interest for aerospace applications.[1] Current state of the art space solar cells are triple junction III-V solar cells, so-called because the device is essentially three distinct solar cells fabricated on top of one another and comprised of elements from groups III and V on the periodic table. These solar cells presently achieve the highest efficiency of converting sunlight into electricity (>30%) under an air mass zero (AM0) solar spectrum, and recent developments have shown outstanding efficiency employing up to six junctions[2]. Silicon solar cells have also found use in space and are currently powering the International Space Station (ISS). In addition to these existing technologies, perovskites would be a logical addition to the space photovoltaic repertoire if it can be determined how to best design a cell/module/panel to operate within the harsh conditions of the space environment and furthermore, exploit their easy-to-manufacture nature in space. Presently, single junction and tandem junction perovskite solar cells (PSCs) have been demonstrated at >25% power conversion efficiency when measured with the solar spectrum on Earth (AM1.5), equating to about 23% using space's AM0 spectrum. Perovskites have a tunable bandgap based upon the composition, and in their wide bandgap form reaches higher efficiency than any other thin film technology enabling hybrid tandems of perovskites on top of Silicon (with record efficiency of 29.8%), or other suitable lower bandgap bottom cells. It is likely that several technologies involving perovskites will be developed with over 30% efficiency in the near future.

The thermal, vacuum, and humidity challenges must be overcome before PSCs can be implemented into space solar arrays. Prior to widespread use in the space environment, solar cells must successfully pass rigorous AIAA-S111 space qualification testing.[3] However, these specifications were designed to address Si and III-V based materials. Perovskites present unique challenges, therefore, their space qualification standards may need to be reconsidered. A chief example of a necessary adjustment is in the radiation standards. AIAA S-111 standards require solar cells be exposed to $1x10^{16}$ fluence of 1MeV electrons per square cm (e^-/cm^2) and $1x10^{13}$ fluence of 3MeV protons per square cm (p^+/cm^2).[3] These fluences have been aptly selected such that the particles impart their energy within the absorber layer of the material providing a valid indictment of the material response. These same particle energies have been shown to heal perovskites due to localized thermal effects combined with the low crystal formation energy in perovskites. [4,5] For perovskites, it may be more appropriate to utilize lower energy protons which in this case are still fully penetrating due to the thinness of perovskite devices.

Radiation concerns are closely related to selection of cell packaging, including the substrate. Any ground-based testing and validation should implement substrates that can endure harsher radiation without significant loss in optical qualities. Soda lime glass or borosilicate substrates commonly used in lab perovskite preparation are insufficient for space application due to darkening color centers from ionic displacement by high-energy particles during radiation exposure.[6] These color centers reduce light intensity and leave the substrate more susceptible to fracture. Instead, for space, alternatives such as ceria-doped borosilicate, quartz, Kapton, Mylar, or others can be explored. The primary considerations for substrate selection include high transparency before and after radiation exposure, low mass, thermal resilience, coefficient of thermal expansion (CTE), and low values of water vapor transmission rate (WVTR) to best suit humid conditions before launch. In preparing devices for MISSE-15 we made informed materials down selection to increase our likelihood of achieving long duration stability of PSCs during exposure to LEO conditions. These down selections included compromises in contact layers as spallation, arcing, and thermal stress are major concerns. When selecting charge selective layers, there are interesting decision points regarding organic interlayers that are sensitive to vacuum and thermal stress but generally yield higher efficiency devices, and metal oxides that are lunar-abundant, easy to deposit, and can double as perovskite encapsulant we opt for an absorber layer that is more robust and capable of high device yield with respectable efficiency. We are most concerned with end of life (EOL) performance to meet mission requirements so high efficiency PSCs that quickly degrade in space relevant environments are inappropriate. As a community we need to conduct as many tests as possible, including ground-based, near space, and long duration flight tests. The best terrestrial PSC will likely not be the best device for operation in space. We need not over engineer for moisture and oxygen sensitivity for a solar cell operating in space, yet we need to consider particle radiation, thermal cycling, and vacuum stability which are not considerations for terrestrial photovoltaics. We need to develop intuition about various chemical compositions, device structure, contact performance and durability in space. That intuition can be data-based thanks in part to space simulation and testing platforms such as high-altitude balloons, commercial lunar lander payloads -through the Commercial Lunar Payload Services or CLPS program, CubeSats to examine LEO and GEO performance, and/or the MISSE platform.

One of the greatest challenges for perovskites is moisture induced degradation and this can be fully circumvented by in-space manufacture of perovskite solar arrays. Perovskites are salts and are susceptible to degradation when water is introduced during or after the manufacturing process. [7,8]

Additionally, oxygen acts as a catalyst to degradation. Mere hours in a humid environment can cause unencapsulated devices to be completely destroyed. [9] Although, our investigations indicate that encapsulation in space qualified DOWSIL 93-500[10] has been shown to prevent any detectable changes in chemical stoichiometry of encapsulated samples at over 880 hours of damp heat (30 ± 5^{o}C and 95% relative humidity). Nevertheless, full fabrication in space avoids this degradation mechanism entirely and eliminates the need and subsequent mass of encapsulants or coverglasses.

There is great interest at NASA to leverage in-space manufacturing. The primary objective is to develop technologies and processes requisite to enable on-demand manufacturing capabilities for long duration space missions. These technologies include additive manufacturing, in-space recycling, and in-situ resource utilization. Made In Space Inc and additional partners from the in-space manufacturing community are currently working on On-Orbit Servicing, Assembly and Manufacturing 2 (OSAM-2) which will 3D print two beams that will unfurl a high efficiency operational solar array while orbiting Earth.[11] In-space manufacturing enables on demand fabrication, repair and recycling which can benefit critical systems, habitats, and maintenance requirements.

Due to the thinness of perovskite devices, a 1 MW solar array could be printed in space while transporting a modest 12 kg of condensed absorber material to orbit. That mass combined with the recent vast reduction in launch costs of materials ($3500/kg) results in a mere $0.10/W costs for the absorber material if a module level efficiency of only 15% could be produced at scale. It is feasible that high power conversion efficiency PSCs can be fabricated via vapor deposition in space. In-space evaporation of perovskite solar cells would leverage the existing vacuum of space in which the perovskite absorber layer would be crystallized, passively annealed from exposure to sunlight to reach 120 ^{o}C, achieving a high-quality film. Subsequent layers would follow sequentially, and laser scribing could be used to define cell areas and sinter printed electrical interconnects to create high voltage arrays. Target substrates are flexible and have high light transmission and thus can be rolled and stowed in a launch vehicle, then engage with the in-space deposition system to be unfurled for PSC fabrication processes. These substrates could include fluorinated ethylene propylene (FEP) with long histories of space applications in thermal management blankets, or clear polyimide. FEP has the mechanical toughness, electrical reliability, chemical compatibility and durability that makes FEP an ideal solution.

The future of implementing perovskites photovoltaics in space is promising, further so is manufacturing these solar cells in space. Perovskite devices demonstrate the most promise for large area high voltage arrays and SmallSat or CubeSat outer planetary missions under low light intensity low temperature conditions.[12] Our preliminary investigations and those of the greater perovskite space research community indicate that PSCs are capable of surviving in the space environment and are thus a promising solution to the growing demand for high voltage capable low-cost solar arrays for operation in space. There exist innovation opportunities that the greater community can contribute to so that we may realize this technology and create the next generation of space solar cells. In general, the space photovoltaics community is always striving to achieve increased cell efficiency, reduced cost, reduced weight and improved radiation tolerance. Perovskites are uniquely positioned to achieve in all arenas and provide technological advancement to aid us in the exploration of the next frontier.

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