Prospect of off-planet outposts spurs interest in space resources

Stakeholders in space exploration consider implications of a transition from science fiction to science fact.

An apparent confluence of political will and technological readiness has fans of humankind's expansion beyond Earth hopeful that their dreams may soon become reality. Alongside a rise in missions to the Moon by agencies and private companies in the US, Europe, China, Japan, India, and Russia, commercial sectors are buzzing with related activities. And various governmental and nongovernmental bodies are strategizing about environmental, ethical, legal, sociological, and other issues of space utilization and colonization.

With interest in space travel growing—spurred in part by billionaire entrepreneurs such as Jeff Bezos and Elon Musk—enthusiasts say the time is right to figure out how to use space resources, including water, solar power, and lunar regolith. Doing so would expand space exploration, increase commercial activities in space, and lead to technological advances for humanity, says Angel Abbud-Madrid, director of the first graduate degree program in space resources, which he and colleagues launched last year at the Colorado School of Mines. (For more about Abbud-Madrid's career path, see the interview at http://physicstoday.org/abbud-madrid.)

Have water, can explore

The only space resource exploited to date is the view of Earth from orbit for such applications as global positioning systems, weather prediction, communications, and science missions. A few years ago the prospect of mining asteroids for platinum and other metals to use on Earth was "the rage," says George Sowers of the Colorado School of Mines. But the business case didn't hold up. One exception might be rare-earth elements, but in the near to mid term, he says, "bringing stuff back to Earth is not economically viable." For now, the focus has shifted to using space resources *in situ*.

Water is a primary target resource in space. Electrolyzed into hydrogen and oxygen, it becomes fuel that could replenish satellites in orbit and propel rockets for exploring the solar system and returning to Earth. Astronauts and space tourists could drink water, use it for gardening and hygiene, and shield themselves from ionizing radiation with meter-thick sheaths of it around habitats or spacecraft.

In 2016 rocket manufacturer United Launch Alliance announced that the company would buy liquid oxygen and hydrogen propellants in low-Earth orbit for $3000/kg. Sowers made that offer in his previous job as ULA chief scientist. He says that a mining company could be profitable at that price, and many companies have begun working toward it. NASA and other space agencies are likely to be key initial customers.

The cost for a rocket to escape Earth's gravity is about $4000/kg, Sowers estimates. With humans aboard, the cost skyrockets, to "maybe as high as $1 million per kilogram," he says. That's because of the additional cargo—water, food, systems for pressure, waste disposal, and so on—needed to keep humans alive and return them to Earth. Once the requisite prospecting is completed and technologies are developed, space-sourced propellants would dramatically reduce the cost of every activity in space, including exploration beyond the Moon, Sowers says.

One of the great discoveries of planetary science is that water ice abounds in the solar system, says Sowers. It exists on asteroids and at the poles of Mercury, the Moon, and Mars. Ice in the permanently shadowed regions of the Moon is a focus of NASA's next manned lunar mission (see PHYSICS TODAY, July 2019, page 22). But details about its condition are sparse: How deep is the ice and how is it distributed? How dirty is it? How can it best be excavated?

Dale Boucher is CEO of Deltion Innovations, a Canadian company that specializes in robotics for space mining. Lunar surveys to date indicating the presence of hydroxyl bonds and possibly water have about 5-kilometer resolution, he says. The next stage is to drill for samples. "We need to send probes to prove that the lunar reconnaissance signatures are actually water," he says. The mechanical, thermal, and chemical properties of the ore bodies will determine the equipment needed for mining.

Water could be mined by heating *in situ* either the Moon's surface or subsurface or by first extracting and then heating ice to release and capture water vapor. Solar power—the preferred energy source for activities on the Moon, although nuclear fission is also being

A ROBOTIC ROVER IS TESTED IN A BIN OF SIMULATED SPACE DIRT at NASA's Kennedy Space Center in Florida. The robot is called RASSOR 2.0—the Regolith Advanced Surface Systems Operations Robot.

discussed—could be tapped for the mining process and for electrolyzing the water and liquefying the oxygen and hydrogen.

LaNetra Tate, Game Changing Development Program executive at NASA headquarters in Washington, DC, leads a team that is working to demonstrate the extraction of polar ice on the Moon and its conversion to usable water. Her team is also pursuing the extraction of oxygen from the lunar soil, or regolith. Many challenges relate to testing equipment in simulated lunar environments and figuring out how to create operations on the lunar surface, she says. "Many things we can figure out from here, but nothing is better than doing it there."

Researchers around the world are exploring how to use the lunar regolith. It resembles tiny bits of broken ceramics—it has jagged edges and is highly abrasive. One idea is to use silicates from lunar regolith as a raw material for constructing solar panels. Oxygen, which by mass makes up more than 40% of the regolith, could be extracted and used for breathing or for rocket fuel.

With 3D printers, regolith—alone or with added polymers—could be formed into almost anything in space. "It's very feasible," says Robert Mueller, cofounder of Swamp Works, a technology innovation lab at NASA's Kennedy Space Center. "You can melt it and make aerospace-grade composite basalt glass materials. You could build rockets or rocket parts."

As robots become more autonomous, space activities will become economically viable, says Philip Metzger, a planetary scientist who moved to the University of Central Florida after a 30-year career at NASA. And when robots can build robots, it will become viable to build things on the Moon, "because you won't have to launch everything from Earth."

The solar wind deposits helium in the lunar regolith; a small fraction (10–30 parts per billion) is helium-3 and could

conceivably be extracted and transported to Earth for fusion energy production. "One shuttle's worth of helium-3 could power the US for a year," says advocate Clive Neal, a geologist at the University of Notre Dame. He concedes, though, that the technology doesn't exist yet.

Space-based industry

John Mankins, who worked at NASA for 25 years, is president of the California-based R&D consulting startup Artemis Innovation Management Solutions. He champions a half-century-old idea: Collect sunlight in space, convert it into electricity with photovoltaic arrays, and use solid-state electronics to convert it into microwave energy; a coherent array of transmitters would send the beam to Earth. The allure is that it would be an inexhaustible source of green power and would therefore help mitigate climate change on Earth.

In space the light intensity would be much higher than on Earth's surface, since the atmosphere absorbs from 40% to 90%. Simpler antenna arrays on the ground would collect the power. From geosynchronous orbit about 36 000 kilometers away, with a transmitter diameter of 1.8 kilometers and a wavelength of 12 centimeters, the beam diameter at Earth would be about 6 kilometers, says Mankins.

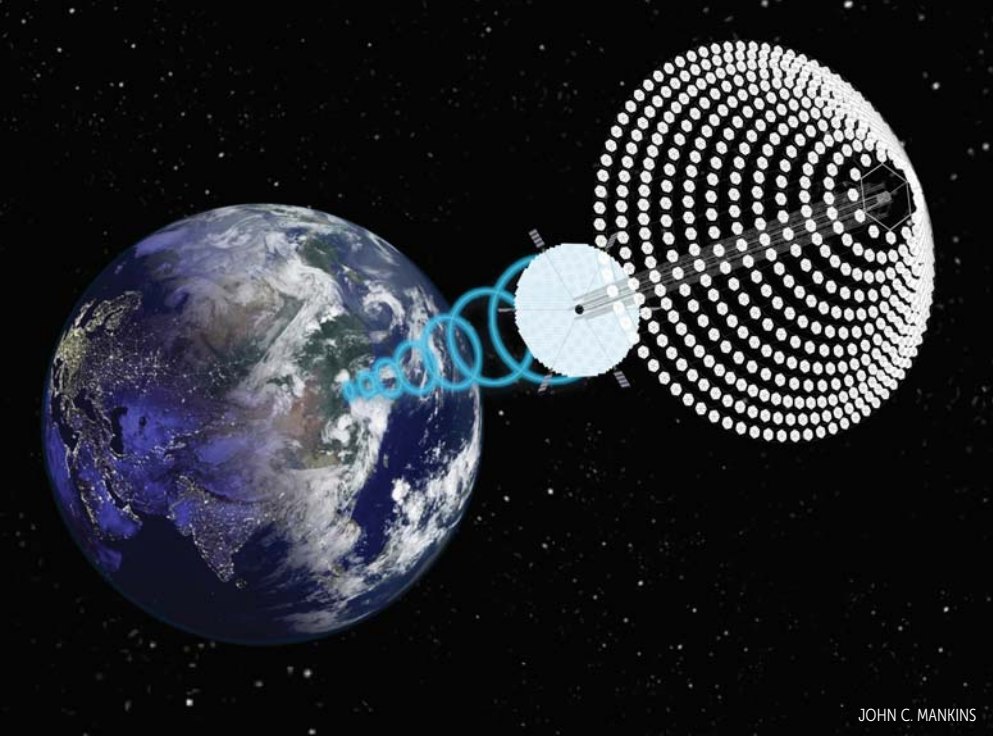
COLORADO SCHOOL OF MINES

MINING WATER ON THE MOON: In experiments to simulate mining on the Moon, concentrated solar energy is used to release water vapor from an icy lunar regolith simulant.

Disturbance to terrestrial activities would have to be avoided, says Sowers, and "you also have to worry about people's perceptions of safety." Launching large solar power satellites from Earth is impractical, he continues, "but if you can build them in orbit, with materials from the Moon, the disadvantages go away."

Solar power from space or helium-3 for fusion would both be "positive outgrowths of developing the Moon," says Sowers. "They are ways to preserve our Earth." Metzger puts it more strongly: "If we get energy, we can solve all the other global and environmental problems."

The 1967 United Nations Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space binds parties to use the Moon and other celestial bodies only for peaceful purposes and specifies that space exploration should be for the benefit of all countries; as of this June, 109 countries—including the US—are signatories. In 2015 the US passed the Commercial Space Launch Competitiveness Act, which explicitly allows exploitation of space resources. It is typically interpreted as "you can keep what you pick up, but you can't claim terri-



A SCHEME TO BEAM SOLAR POWER entails collecting sunlight and beaming it to Earth. An array of mirrored heliostats (conical structure) collects the sunlight, and a photovoltaic array (disk) converts it into electricity, which is then converted into a coherent microwave beam and sent to receivers almost anywhere in view on Earth. The image depicts the SPS-ALPHA, or Solar Power Satellite by means of Arbitrarily Large Phased Array.

tory." Luxembourg followed with a similar law in 2017.

In a bid to become the European hub for space resources, Luxembourg has created a business environment to lure space-related companies. It offers political support and has set aside €200 million ($224 million) to subsidize them. So far, more than 20 such companies are based there. "About 2.5% of the country's GNP is in the space industry," says Pete Worden, a retired NASA scientist who now serves on the Luxembourg government's space resources advisory board. "They felt that if they could stake a claim in space resources, they'd be in good economic shape for the future."

The United Arab Emirates is also looking to space to diversify its economy and for educational and training purposes. The country aims to create a settlement on Mars by 2117. It would be a joint effort with international stakeholders, says Mohammed Al Ahbabi, director general of the country's five-year-old space agency. Toward that goal, the UAE is building a simulated Mars environment in Dubai for experiments in space-resource utilization and other activities that would be necessary for living on the red planet. On 25 September the country will send its first astronaut to the International Space Station, and next year it will launch a spacecraft that will orbit Mars. "We want to become a meaningful contributor to humanity's exploration efforts in space," Al Ahbabi says.

Metzger cites a 2016 study by the semiconductor industry predicting that by mid century, if current trends continue, computing will grow to the point that it alone will consume the entirety of today's global power production. "We either destroy the environment, limit the amount of computing, or we move off the planet," he says. Data is the easiest thing to move, "so we can create server farms in space and send the data back to Earth." By moving a large portion of the industrial footprint to the Moon, "we clean up our planet."

Ground rules

Matthew Weinzierl, a Harvard Business School professor who studies the public and private space sectors, says that for new space-based activities to develop to any sizeable scale would require "a spectacular breakthrough along the lines of manufacturing or solar energy from space." Space tourism could lead to a "virtuous cycle of space services development," he says. But many uncertainties remain. "It's hard for me to see meaningful [lunar] settlement over the next several decades," he says, adding that a limited station, such as those on Antarctica, seems more likely. Ian Lange, an

economist at the Colorado School of Mines, doubts that the space resources and travel industries could maintain funding through an economic downturn. Still, he says, if launch costs continue to drop, "it will be a game changer as it will become cheap to start putting infrastructure in space."

When technical revolutions lead to economic revolutions, social upheaval often results, says Metzger. "It takes time to find justice. The same will happen when we get industry off the planet." It's not too soon to be "intentional" about expanding to space, he says, both to benefit humankind and to avoid war.

The Hague International Space Resources Governance Working Group, which comprises representatives from governments, academia, and companies, is putting together recommendations intended to set a baseline for future space-related activities. Among the topics the group is addressing are the sharing of benefits, regard for the interests of all countries and humankind, creation of safety zones in space, and monitoring and avoidance of harmful effects of space utilization.

Michelle Hanlon, a space lawyer in Mississippi and a member of the Hague working group, says the biggest issue internationally at the moment is what it means that space is the province of all humankind. Some countries believe that if you mine resources, the benefits should be shared with the entire international community, she says. Others, like the US and Luxembourg, say that you can keep what you extract. "We can't develop laws until we see how technology shakes out," she says. "The Moon will get crowded. What happens if two companies set their sights on the same crater?"

Technical, social, political, economic, and other issues related to space resources are addressed in the Colorado School of Mines' new space resources program, which offers certificates and master's and PhD degrees. This fall 30 incoming students are joining the 45 in last year's inaugural group. The bulk of the students are mid career and participate remotely from 12 countries on 4 continents. "My classmates have incredible roles at NASA, SpaceX, startups, and more. It's incredible interacting with them," says Adam Janikowski, an investment banker in Hong Kong who is enrolled as a master's student. "I want to marry my engineering and financial backgrounds with this space education to give financial advice" to space-focused companies.

According to Michael Waltemathe, a theologian at Germany's Ruhr University in Bochum who works on space exploration issues, "History has shown that as soon as technology makes things possible, people will do the new things." Some groups are against space exploration for religious reasons, he says. The main arguments against it are that for the same money we should clean up our planet and feed the poor, not explore. But, he says, exploration could also be used to mitigate inequality. People from countries that can't afford their own launches could partake in future economic advantages by, for example, remotely controlling space-based robots. "We can't stop exploration, so we should set up rules beforehand to benefit as much of humankind as possible."

Toni Feder