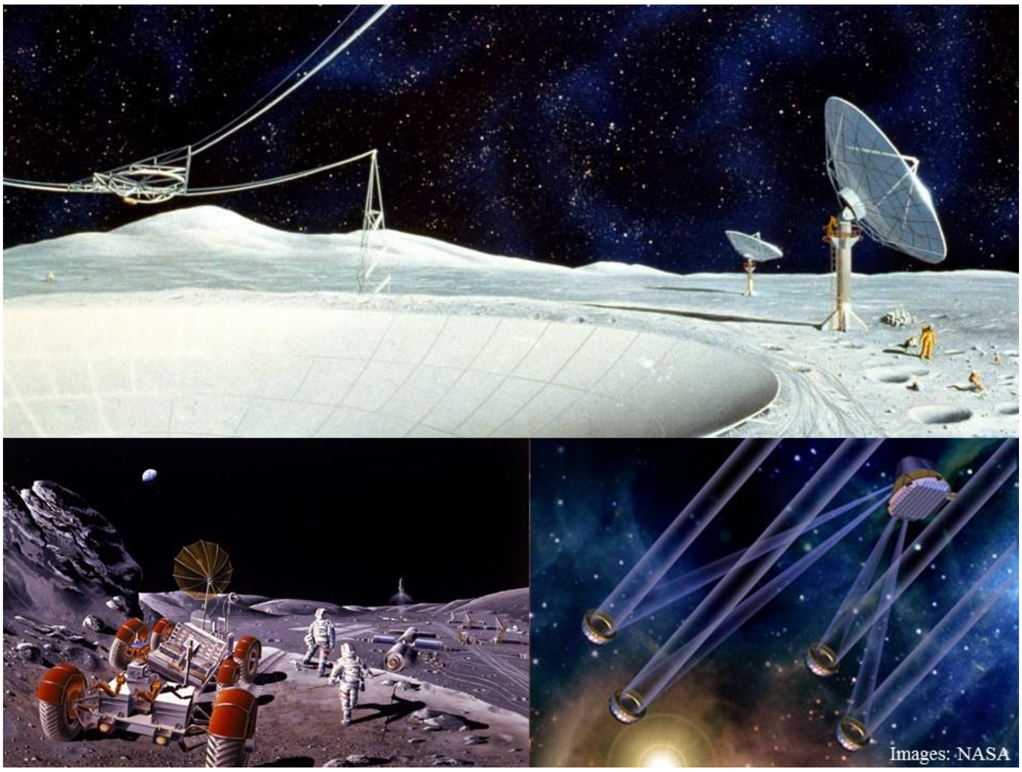
Royal Astronomical Society Specialist Discussion Meeting:

The use of Extraterrestrial Resources to help Facilitate Space Science and Exploration

Friday 8 April 2016

Organisers: Professor Ian Crawford (Birkbeck College London), Dr Martin Elvis (Harvard Smithsonian Center for Astrophysics), and Dr James Carpenter (European Space Agency)



To-date, all human economic activity has depended on the material and energy resources of a single planet, and it has long been recognized that developments in space exploration could in principle open our closed planetary economy to external resources of energy and raw materials. Recently, there has been renewed interest in these possibilities, with several private companies established with the stated aim of exploiting extraterrestrial resources. Space science and exploration are among the potential beneficiaries of space resources because they may permit the construction and operation of scientific facilities in space that would be unaffordable if all the required material and energy resources had to be lifted out of Earth's gravity. Examples may include the next generation of large space telescopes, sample return missions to the outer Solar System, and human research stations on the Moon and Mars. This meeting will explore these issues, and will provide an opportunity for space scientists and emerging space industrialists to discuss mutually advantageous possibilities.

ABSTRACTS

(Ordered as on the programme)

Martin Elvis (Harvard-Smithsonian Center for Astrophysics):

What can space resources do for astronomy?

Within a few years commercial transport to private space stations, for so long a will ‘o the wisp, will become reality. By 2017 at least two companies, SpaceX and Orbital, will be offering private rides to orbit and Bigelow Aerospace will have its first large orbiting habitat. Commercial exploitation of space resources could well begin 5 years after that. Given the 20-year gestation periods for large space telescopes, the impact of commercial space development becomes an immediately relevant issue as we plan the next generation of observatories. I will discuss how commercial space could change how we design missions and give specific examples of valuable developments.

Paul Spudis (Lunar and Planetary Institute):

The Moon as an enabling asset for spaceflight

A human return to the Moon can be accomplished for reasonable investment within the next decade. Uniquely among near-term space destinations, the Moon’s proximity permits us to emplace infrastructure prior to human arrival through the use of robotic teleoperations controlled from Earth. The quasi-permanent, grazing incident sunlight of the lunar poles allows us to generate energy for constant operations and results in a benign surface thermal environment. Water ice near the poles can support human life, protect the crew from galactic and solar radiation, and serves as a medium of energy storage. But most importantly, the water may be converted into cryogenic oxygen and hydrogen, the most powerful chemical rocket propellant known. These energy and material resources of the Moon allow us to develop cislunar space, the zone of space in which more than 95% of our satellite assets reside. A permanent, transportation infrastructure based in cislunar space allows us to reach any point in space, including human missions to the planets.

Olivier de Weck (Massachusetts Institute of Technology):

Detour to the Moon: How lunar resources can save up to 68% of launch mass to Mars

Simple logistics strategies such as “carry-along” and Earth-based “resupply” were sufficient for past human space programs. Next-generation space logistics paradigms are expected to be more complex, involving multiple exploration destinations and in situ resource utilization (ISRU). Optional in situ resource utilization brings additional complexity to the interplanetary supply chain network design problem. This talk will present an interdependent network flow modeling method for determining optimal logistics strategies for space exploration and its application to the human exploration of Mars. It is found that a strategy using lunar resources in the cislunar network may improve overall launch mass to low Earth orbit for recurring missions to Mars by 68% compared to NASA's Mars Design Reference Architecture 5.0, even when including the mass of the in situ resource utilization infrastructures that need to be pre-deployed. Other findings suggest that chemical propulsion using liquid oxygen/liquid hydrogen, lunar in situ resource utilization water production, and the use of aerocapture significantly contribute to reducing launch mass from Earth. A sensitivity analysis of in situ resource utilization reveals that, under the given assumptions, local lunar resources become attractive at productivity levels above 1.8 kg⁄year⁄kg in the context of future human exploration of Mars.

This talk will be based on the following recent publication:

Ishimatsu T., de Weck O., Hoffman J., Ohkami Y., Shishko R., "Generalized Multi-Commodity Network Flow Model for Space Logistics in the Earth-Moon-Mars System", *Journal of Spacecraft and Rockets*, DOI: 10.2514/1.A33235, published online on 5 November 2015.

Phil Metzger (University of Central Florida) and Kris Zacny, Kathryn Luczek, and Magnus Hedlund (Honeybee Robotics):

Using ice for planetary surface propulsion: a strategic technology to initiate space industry

There is broad consensus that water is the most strategic resource for initial space mining efforts. Potential customers for water obtained in space include government space agencies conducting scientific exploration as well as commercial satellite companies wishing to boost spacecraft from Low Earth Orbit to Geosynchronous orbit more affordably. Water can be electrolyzed into hydrogen and oxygen for high performance rocket propellant. For human-tended missions, water can also be used as radiation shielding. The economic problem is that infrastructure will be needed in space to mine the water, electrolyze it, cryogenically store it, and transfer it into other spacecraft. This infrastructure (including power, thermal management, command and control, and other systems) will be massive and costly. Is not clear whether there will be adequate customer demand in the initial space water market to repay startup costs including a finance rate with risk premium. A first step with lower startup cost is needed, such as using water directly as the propellant without electrolysis, heating it to steam with concentrated sunlight. This reduces the infrastructure needed in orbit and enables smaller applications. After thus establishing the simplest water economy in cis-lunar space, more complex infrastructure can develop over time. An even smaller first step is to develop these technologies for planetary science missions, and to apply them in a cis-lunar water economy later. On surface lander missions on Europa or the ice caps of

Mars, for example, all the equipment will be contained inside a single spacecraft, including the ice mining, water storage and heating, and steam propulsion systems. Utilizing in situ water for propulsion of planetary surface missions will mature the technologies and prove to potential investors that they will also work in a cis-lunar economy. This will also enable better planetary science since the planetary landers will be able to move about without exhausting their propellant, dramatically extending the value of these missions. With this in mind, we have begun developing the necessary technologies through a series of demonstrations and analyses, including detailed thermodynamic modeling of steam propulsion systems. The specific impulse of steam is found to be as high as 160 seconds, which is not as good as the 450 seconds for hydrogen and oxygen but is still not bad. We have shown that a 6U CubeSat-sized spacecraft using steam can hop on the order of a kilometer on Mars or multiple kilometers on Europa or Pluto. Depending on the volume of the water tank, a 155 kg lander (Mars Phoenix Lander-class) can hop tens or even hundreds of kilometers on Europa. Using a radioactive decay source for mining and heating the water, replenishment of hot propellant can occur in just days. Hopping landers as well as hopping drones operating off the main lander are possible with this architecture.

Sebastian Ernst (Deep Space Industries):

Industrial space exploration: Commercial asteroid missions aiding scientific inquiry

[Abstract not yet received]

Jim Keravala (Shackleton Energy Company):

Accelerating space science and exploration in partnership with commercial resource utilisation

Access to lunar based resources is a cornerstone requirement for the balance of our terrestrial economy and civilization as well as sustained expansion in space. The establishment of propellant depots at key locations in near Earth space enables reusable transportation in space to become a viable proposition. Establishing the cis-Lunar highway required to access lunar sourced water from the cold traps of the polar craters provides the backbone infrastructure for exponential growth for a space-based economy. With that infrastructure in place, space-based solar power generation systems, debris mitigation capabilities and other necessary infrastructure can be established on a fully commercial basis.

Shackleton Energy was founded from the space, mining, energy and exploration sectors to meet this challenge as a fully private venture. With a set of industrial objectives in space, the demarcation between commerce, science and exploration dissolves. Each is essential to the fulfilment of the other. Commercial and industrial activities in space cannot occur in a scientific and technical development vacuum (no pun intended). Extensive exploration and research is necessary to understand the implications and limits of industrial capability. On Earth, we have carried out industrial and commercial activities in the assumption that cost of extraction is a burden to be left to the planet to bear. In space, operational self-interest turns all industrialists into ardent environmentalists. Engineering and mining activities cannot occur effectively in a suspension of lunar or asteroidal regolith. Enhanced science and exploration is required to solve these and other challenges.

The intensity of scientific exploration required for industrial expansion lends itself to a strong partnership between the scientific, exploration and commercial sectors to operate together. Lunar and asteroidal assays use the same tools for scientific research. Composition, distribution, processing, geologic history, mineralogy and every other discipline imaginable encourages mutually essential collaboration. Building upon this relationship the opportunities for building great observatories in space, studies of our near space environment, the human condition in space and a host of other scientific endeavours will benefit from the offset of scientific infrastructure capital investment.

This presentation proposes some principles and opportunities for commercial-scientific program of exploration.

James Carpenter (European Space Agency):

Lunar resources: Exploration enabling science

Many space agencies and private entities are looking to lunar resources, extracted and processed in situ, as a potentially game changing element in future space architectures, increasing scale and reducing cost. If this were to be the case then the opportunities for science in space would be greatly enhanced. However, before any decisions can be made on the inclusion of resources in exploration roadmaps of future scenarios some big questions need to be answered about the viability of different resource deposits and the processes for extraction and utilisation. The missions and measurements that will be required to answer these questions, and which are being prepared by agencies and others, can only be performed through the engagement and support of the science community. In answering questions on resources data and knowledge will be generated that is of fundamental scientific importance. In supporting resource prospecting missions, the science community will de facto generate new scientific knowledge. Science enables exploration and exploration enables science.

Simeon Barber[1], Francesco Rizzi[2], Matteo Savoia[2], James Carpenter[3], Richard Fisackerly[3]:

PROSPECT: ESA's lunar resource prospecting tool as a precursor to lunar science and exploration

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It is well understood that accessing and utilising resources on the lunar surface could facilitate space science and exploration through providing materials to construct and operate new facilities both for lunar science and onwards exploration. Of all these potential resources, cold trapped water in polar regions is perhaps the most exciting in terms of accessibility and utility. The idea that the Moon's poles contain a vast repository of water ice is not new. Yet although a number of recent orbital measurements and the LCROSS impactor have provided further indirect evidence, many uncertainties remain concerning the occurrence, distribution and accessibility of this putative water. Indeed, one of the few areas of consensus appears to be that the unanswered questions are best addressed through landing spacecraft in lunar polar regions and prospecting in-situ for lunar water and other volatile resources.

PROSPECT is the name given to ESA's exploration product for accessing, extracting, processing and analysing lunar volatiles. PROSPECT (Package for Resource Observation and In-Situ Prospecting for Exploration, Commercial exploitation and Transportation) comprises a drill, ProSEED (PROSPECT Sample Excavation and Extraction Device) and a complementary chemical analysis laboratory ProSPA (PROSPECT Sample Processing and Analysis). ESA is working together in cooperation with ROSCOSMOS to realize a first flight opportunity for PROSPECT on-board the Luna-Resource mission in the early 2020s, and is today supporting the design, prototype development and field testing of the package.

The key requirements for PROSPECT are informed by, and seek to provide ground-truth measurements to test, current understanding of remote sensing datasets and modelling studies. PROSPECT shall therefore obtain surface samples (for comparison with orbital infra-red data) and sub-surface samples from depths to 1.2 – 2 m (corresponding to orbital neutron spectroscopy datasets). The samples will be extracted carefully to minimise alteration and loss of the most volatile components, which in practice means handling samples at around 120 K, from extraction up to the point at which samples are sealed within ProSPA.

Once sealed, samples will be imaged for geological context and to provide an estimate of sample size. Then samples will be heated in a controlled manner to release their volatile components as a function of temperature. The data will bear direct comparison with previous analogous studies on Apollo samples, though of course on samples from very different locations on the Moon and with the benefit of ameliorated concerns over potential terrestrial atmospheric contamination.

Optionally, oxygen gas can be introduced during sample heating to perform stepped combustion, generating datasets for comparison with terrestrial isogeochemical studies on lunar samples and meteorites.

A further option is to introduce reducing agents into the ovens during heating, in an attempt to study the efficacy of some of the volatiles extraction techniques that have been proposed in the context of in-situ resource utilisation (for example ilmenite reduction by hydrogen gas).

In all, PROSPECT will seek to ascertain the identity, quantity and isotopic composition of volatiles within polar regolith, as a function of depth down to 1.2 to 2 m. The data obtained will generate new understanding of lunar polar resources and the possible extraction of lunar resources for ISRU. This in turn will inform the design and targeting of future more advanced lunar polar missions such as rovers and sample return, as well as longer term ambitions for lunar bases for science and exploration.

Vibha Srivastava, Sungwoo Lim and Mahesh Anand (The Open University):

Microwave processing of lunar soil for supporting longer-term exploration missions on the Moon

The future of human space exploration involves longer-term stays on the surfaces of other planetary bodies which will necessitate utilization of local resources for building an infrastructure for human habitation and in this context human exploration of the Moon is next obvious step. Lunar soil is considered to be an ideal feedstock for building an infrastructure on the Moon. However, there are significant knowledge gaps in terms of our knowledge of certain chemical and physical properties of lunar soil, which needs to be better understood in order to develop appropriate construction techniques for lunar applications.

For example, understanding of the dielectric behaviour of lunar soil in the microwave spectrum is increasingly being recognized as an important topic of research in the field of Space Architecture. Despite the appreciation of the coupling between the lunar soil and microwave energy, it poses a few challenges to be a main fabrication method in producing a good quality construction material on the Moon. In this presentation, we will review the current status of our knowledge about the potential of microwave sintering of lunar soil for construction purposes on the Moon and discuss our ongoing research in this area. The information from this study may benefit the space science community in understanding the unique characteristics of lunar soil compared to soil/regolith from other planetary bodies including the Earth.

Manuel Grande (Aberystwyth University):

Asteroid mining: What's in it for planetary science

The growth of commercial models for Asteroid and Lunar exploitation presents both opportunities and questions for planetary scientists. We are used to working in an environment where, after decades of lobbying, large agencies organise ambitious missions to address large, pressing science questions. Commercial models offer rapid turn-around, and Missions of Opportunity which might not otherwise arise. However, the very specific data requirements, and the commercial sensitivities of results obtained, will mean that scientists must adopt new attitudes and methodologies. Now is a good moment to start addressing these questions.

Colin Snodgrass (The Open University):

Searching for water in asteroids

Water ice is a valuable resource in space, and its presence in small bodies opens the possibility of extracting it directly rather than lifting it from Earth. Comets contain significant ice but are difficult to reach, while asteroids were traditionally thought of as dry rocks. I will review recent discoveries that show that there is water ice in asteroids (direct detections in Ceres and other large asteroids, and implied in small 'active asteroids'), and discuss the levels at which very weak outgassing could confirm these discoveries and reveal ice in other asteroids, and how we could go about searching for this.

Colin McInnes (Glasgow University)

Near Earth asteroid capture dynamics, material sorting and utilisation for large on-orbit reflectors

A range of strategies for capturing small near Earth asteroids will be presented along with a discussion of the engineering requirements for such ventures. It can be shown that the energy required for capture can be minimised by using the stable manifolds of periodic orbits in the Sun-Earth and Earth-moon systems. Then, the utilisation of metals extracted from such near Earth asteroids will be considered for future space science applications. These include the fabrication of large-scale, thin-film reflectors where the reflector optical properties are engineered to control the shape of the reflector due to billowing from solar radiation pressure. In principle, this allows the fabrication of parabolic reflectors without the need for a mechanical structure.

Michael Johnson[1,2] and Julie McCann[2]:

Replenishing prepositioned Spacecraft-on-Demand printers

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In-situ production of space systems for science, exploration, education and profit is likely to be the preferred method of implementing large scale space systems in the future. The Spacecraft-on-Demand system is being developed to test approaches for realising such systems on orbit for implementing spacecraft, landers and rovers at mg to kg scale.

A terrestrial laboratory based system is currently being refactored as a Prepositioned Orbiting Printer CubeSat (POP/C) to demonstrate production of entire functional space systems on orbit. POP/C is designed to launch with a modular detachable Insulator, Conductor, Energy and Semiconductor CubeSat (ICES/C) materials cartridge to demonstrate production of multiple devices per cartridge.

Although initial POP/C devices are designed to be replenished by replacing a depleted ICES/C with a replacement launched from earth, approaches for refilling expended cartridges with suitable material from the environment are also in the early stages of being explored. The current focus is developing concepts for refilling depleted 'E' reservoirs in different environments.

Ian Crawford (Birkbeck College London):

The long-term scientific benefits of space infrastructure

Utilisation of the material and energy resources of the Solar System will be essential for the development of a sustainable economic and industrial infrastructure in space. Consistent with its usual definition, by space infrastructure I have in mind the development of installations and capabilities that will facilitate wide-ranging human operations in the space environment. Science will be a major beneficiary of such an infrastructure, even if its major elements (e.g. resource extraction activities on the Moon or asteroids, or large-scale in-space construction capabilities) are not developed with science primarily in mind. Examples of scientific activities that would be facilitated by the development of space infrastructure include the construction of large space telescopes, ambitious space missions (including sample return missions) to the outer Solar System, and the establishment of scientific research stations on the Moon and Mars (and perhaps elsewhere). In the more distant future, an important scientific application of a well-developed space infrastructure may be the construction of interstellar space probes for the exploration of planets around nearby stars.