Institution: The Open University		
Unit of Assessment: B9 Physics		
Title of case study: A Wet Moon: A paradigm shift in European lunar exploration policy, business & understanding		
Period when the underpinning research was undertaken: 2000-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof Mahesh Anand	Professor of Planetary Science & Exploration	2014-2021
Dr Simeon Barber	Senior Research Fellow	1997-2021
Dr Simon Sheridan	Senior Research Fellow	1995-2021
Period when the claimed impact occurred: 1 Aug 2013 - 31 Dec 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

It is over 50 years since samples were returned from the Moon, but analysis of Apollo materials still provides surprises about our natural satellite, inspiring a new generation of space missions. Our research on lunar volatiles informed policy changes at ESA, underpins development of novel analysis and water extraction techniques for the space sector and helped to upskill schoolteachers. Impacts on **public policy, commerce and the economy** and **understanding, learning and participation** include: ESA's new EUR1B exploration programme that highlights lunar exploration; award of contracts worth more than EUR40M to companies and subsequent creation of new jobs and development of a continued professional development package for teachers.

2. Underpinning research

Our research develops novel analytical methods to analyse extra-terrestrial samples in the laboratory or *in situ* on space missions. Our findings advance fundamental planetary science, enable human and robotic space exploration, and are applied in new space products.

Laboratory methods: Since 2011, our STFC-funded research has pioneered developments of several new analytical laboratory methods using nano secondary ion mass spectrometry (NanoSIMS), which for the first time not only revealed the presence of significant quantities of indigenous volatiles such as H and Cl in lunar samples but also their potential sources through their isotopic measurements. These findings helped change the 40-year-old paradigm of a 'bone-dry Moon' **[O1]** and further identified the major source of water in the Moon **[O2]**.

Space Instruments: From 2000 to 2014 (funded by STFC), we developed and built a miniaturised analytical instrument, Ptolemy, which flew on the European Space Agency (ESA) Rosetta mission. Ptolemy was designed to study the surface and local atmosphere of the target, comet 67P Churyumov-Gerasimenko. Our instrument successfully made the first *in situ* measurements of water and organic compounds on a comet **[O3]** and demonstrated heterogeneity across the two landing sites and in time **[O4]**.

With ESA funding, we are building on this success and developing the next generation of instruments for missions to the Moon. In this context, in 2017-19 and funded by the UK Space Agency (UKSA), we developed a novel method for analysing extra-terrestrial samples. It enables, for the first time, quantitative determination of multiple gases released through heating, using an order of magnitude smaller samples **[O5]**.

Implications of ISRU: *In Situ* Resource Utilisation is the concept of making use of materials found off-Earth, significantly reducing the mass of a spacecraft and hence its launch cost and environmental impact. Water is the most important such resource: it can be used for human life support (drinking, and a source of breathable oxygen) and can be processed into hydrogen and oxygen as an energy source and rocket propellant. In 2016-20, and funded by STFC, we developed and applied a novel thermochemical method for extracting oxygen and water from 'dry' Moon soil samples to be analysed *in situ* on the Moon by an ESA payload **[O6]**.

3. References to the research

O1. Barnes, J.J., Franchi, I.A., **Anand, M**., Tartèse, R., Starkey, N.A., Koike, M., Sano, Y., & Russell, S. S. (2013) Accurate and precise measurements of the D/H ratio and hydroxyl content in lunar apatites using NanoSIMS. *Chem Geol.* 337-338, 48-55. https://doi.org/10.1016/j.chemgeo.2012.11.015

O2. Barnes, J.J., Kring, D.A., Tartèse, R., Franchi, I.A., **Anand, M**., & Russell, S.S. (2016) An asteroidal origin for water in the Moon. *Nature Communications* 7, 11684. https://doi.org/10.1038/ncomms11684

O3. Wright, I.P., **Sheridan, S**., **Barber, S.J**., Morgan, G.H., Andrews, D.J., & Morse, A.D. (2015) CHO-bearing organic compounds at the surface of 67P/Churyumov-Gerasimenko revealed by Ptolemy. Science 349(6247), aab0673. https://doi.org/10.1126/science.aab0673

O4. Morse, A., Mousis, O., **Sheridan, S**., Morgan, G., Andrews, D., **Barber, S**., & Wright, I. (2015) Low CO/CO 2 ratios of comet 67P measured at the Abydos landing site by the Ptolemy mass spectrometer. Astronomy and Astrophysics, 583. https://doi.org/10.1051/0004-6361/201526624

O5. Verchovsky, A.B., **Anand, M**., **Barber, S.J**., **Sheridan, S**., & Morgan, G.H. (2020) A quantitative evolved gas analysis for extra-terrestrial samples. Planet. Space Sci. 181, 104830. https://doi.org/10.1016/j.pss.2019.104830

O6. Sargeant, H.M., Abernethy, F.A.J., **Barber, S.J**., Wright, I.P., **Anand, M**., **Sheridan, S**., & Morse, A.D. (2020) Hydrogen reduction of ilmenite: Towards an in situ resource utilization demonstration on the surface of the Moon. Planet. Space Sci. 180, 104751. https://doi.org/10.1016/j.pss.2019.104751

4. Details of the impact

Our role in the discovery and understanding of the nature of water in lunar samples, coupled with our development of novel instrumentation for *in situ* analysis at the lunar surface, has underpinned impacts on **public policy (at European and UK level), commerce and the economy,** and **understanding, learning and participation**. The beneficiaries include space agencies, businesses (SMEs and multinationals) and school students and their teachers.

Pathways to Impact are through three routes:

- Using our standing in the scientific community and membership of influential committees to advance European and UK policies on lunar exploration.
- Collaborating with multiple UK and European companies who learned of the application of our expertise in space missions (e.g., Rosetta Lander Philae).
- Developing a research-informed continued professional development package for schoolteachers, accompanied by engagement activities for schools, facilitated by the OU's School of Physical Sciences' Outreach and Public Engagement team.

A. Impact on Policy: Strategies and Implementation of European and UK Space Policies

Our research on lunar volatiles and instrument development has helped to foreground the Moon as a focus for space exploration and strengthened understanding of its potential for human habitation. We have been a key player in ensuring that lunar science and exploration is now embedded within ESA and UKSA roadmaps and that the Moon is a major strategic target for international partnerships.

Strategy Development:

In 2012, the ESA Ministerial Council failed to approve funding for a Lunar Lander because it was of insufficient priority compared with exploration of Mars. Following new discoveries in the field of lunar volatiles, including those made by **Anand [O1, O2]**, ESA started to develop a new lunar exploration strategy, which became a major part of the European Exploration Envelope Programme (E3P). The OU's research played a significant role in developing the programme, as explained by the Lunar Resource Lander Team Leader at ESA (hereafter 'ESA LRLTL'):

> "*the significant impacts that [**Barber**, **Anand** and **Sheridan's**] research on lunar volatiles and instrumentation has had on the European Space Agency's programme of robotic and human exploration […] .there has been the need to build a broad scientific community and political support in Europe on this topic, to which OU has been contributing actively […] [the OU] participates heavily in advisory scientific teams and groups [and our] inputs have*

supported ESA to define its strategy for lunar science and for resources utilization […] which at the end contributed to the approval of a new batch of lunar studies and developments for several tens of millions Euros at the ESA Ministerial Council in 2016 and in 2019" **[C1]**.

Anand's lunar research has established him, since 2014, as the resident expert on lunar science and exploration on the highly influential European Space Science Committee (ESSC), in which role he led assessment of the E3P proposal. The ESSC Chair states:

"*the ESSC has a unique position in Europe providing independent scientific advice on space science matters to ESA, the European Commission (EC), national space agencies [...]* ***Anand*** *was instrumental in independently reviewing the ESA's European Exploration Envelope Programme (E3P) proposal and helping shape the resulting recommendations to the ESA directors and Ministers. The proposal, presented by ESA to the Ministerial meeting in 2019, for the first time included explicit funding for lunar exploration […], which eventually was approved by the Council of Ministers"* **[C2]**.

Strategy Implementation:

Implementation of lunar science and exploration activities at ESA has been strongly influenced by the novel analytical techniques we established through laboratory analysis of lunar samples **[O1, O5]** and applied the findings towards developing payload instruments for space missions **[O3, O6]**. The ESA LRLTL states:

"*we learned of the Open University's instrumentation for volatiles analysis through their research in the ESA Rosetta comet mission […] OU is also very much involved [in ESA's lunar strategy] implementation via the development of different sample analysis instruments for lunar landers. Among the eight main scientific areas prioritised by ESA, four are fed by research and development work at OU […] The OU team's research and expertise has developed for ESA new technologies for lunar science and exploration, and specifically for finding, identifying and quantifying water ice and other important materials. These are recognised internationally as state-of-the-art technologies, and have enabled ESA to negotiate with other space agencies to put OU-built instruments on their lunar landers. The research has therefore enabled Europe to play a key and visible role in lunar science and exploration missions, on an international stage"* **[C1]**.

Our instrumentation and methods for *in situ* analysis have enabled ESA and UKSA to establish new international collaborations. [Text removed for publication.] **[C3]**.

Such opportunities include ESA payloads on the Russian Luna-27 lander and in NASA's return to the Moon with the Artemis program.

Our research into ISRU is already showing impact on strategy. The ESA LRLTL states

"*the novel techniques and instruments developed at OU are increasingly in demand on the international stage […] ESA is already in negotiations with other space agencies including NASA (US) and JAXA (Japan) to develop future instruments (via OU) for future missions to the Moon. ESA may work with OU on new instrument technologies such as instrumented drills and ISRU instruments, like in the frame of the future European Large Logistics Lander (EL3) mission currently under study by ESA. This might open up new areas of robotic and human exploration through lowering the costs of prolonged presence in space"* **[C1]**.

B. Impacts of our analytical technique developments upon Business and the Economy

By developing world-leading capability in analytical instruments for prospecting and analysing water (volatiles) on missions to the Moon underpinned by our body of research, we have created multiple strategic opportunities for European and UK businesses of various sizes which have already started delivering significant growth and new income streams. We have collaborated with the Italian company Leonardo to develop the PROSPECT payload for ESA. Their Head of Space explains:

"*we did not have the expertise to develop the sample analysis instrument for PROSPECT, and so we entered into discussions with OU as recognised experts in this field, and agreed to collaborate […] with OU responsible for the development activities for the sample analysis instrument called 'ProSPA' which is complementary to the Leonardo-led drill 'ProSEED' […]. The strength of the bidding team and our proposal was recognised when ESA awarded an EUR8,400,000 [12.07.16] contract to Leonardo in 2016 for PROSPECT development model*" **[C4]**.

The collaboration successfully delivered this phase of the project and submitted its proposal for the next phase. The Head of Space said

> "*ESA awarded a contract in January 2020 to Leonardo for a [further] EUR31,500,000 for the development of PROSPECT flight model. Again, OU is the major project collaborator […]. The research of OU into lunar samples, ices and volatiles and mini science laboratories has been very important for us. Our collaboration with OU has led to these two very important contracts for the company and has secured a role for us in a new and the growing market for lunar exploration missions which previously we had not been involved in. The employment of highly skilled staff is a significant part of the cost of a space product, and so contracts of this value secure many tens of existing and new jobs in our company and in the supply chain in the various countries that support our work on PROSPECT*" **[C4]**.

Four UK SMEs are key players in PROSPECT, supplying services and/or technology. One example is Fluid Gravity Engineering (FGE) Ltd. The FGE Company Director says:

> "*We were missing out in the growing field of lunar exploration because our expertise in atmospheres was thought to be irrelevant on the airless Moon. However, in 2011 your team at OU approached us in the context of your research into the in situ analysis of lunar samples, and suggested that our proprietary techniques could be developed to model the artificial atmosphere created by the exhaust gases emitted by a lunar lander. Our subsequent R&D collaborations with OU have proved the value of these approaches [text removed for publication]. This financial benefit, and the fact that these projects are prestigious and exciting to work on, has been significant in retaining our workforce of 24 highly skilled employees. We have also been the only SME invited to attend high-level strategy planning meetings convened by ESA with multi-national space conglomerates. I do not believe that we would be pursuing this new line of business without our association with OU's research into lunar volatiles and instrumentation techniques*" **[C5]**.

A second UK SME example is Dynamic Imaging Analytics. Its CEO states:

> "*We submitted a proposal to OU to use our novel 3D camera technology in their PROSPECT project looking for water in lunar samples. The resulting collaboration in 2016-17 enabled us to make our first step into the European space sector, which is an important step for us as a new tech start-up […]. The collaboration with OU's team led to us developing a family of new camera products for the space market to support exploration for water on the Moon […] this new business line has secured multiple income streams comprising more than half of our total income in the period 2016-2020, underpinning our sustainable growth from 1 to 5 employees*" **[C6]**.

Belgian SME Space Applications Services has developed new business lines through its interaction with our research. Its Technologies, Applications & Research Manager states:

> "*We were fundamentally lacking sufficient scientific insight and understanding of the key scientific motivations and priorities for lunar exploration. Through a series of discussions and interactions with OU (Dr. Simon **Sheridan** and Dr. Simeon **Barber** in particular), we realized the prominence of volatiles detection as an overarching area of interest in the community, with extremely concrete and promising middle to long term commercial prospects*" **[C7]**.

They further state that the first funded collaboration with us received the following evaluation:

> "*This is an amazing project where the team has delivered exceptional results with significant immediate or potential impact […]OU's novel techniques, technologies and partnership has played a part in helping Space Applications Services secure funding to the tune of nearly EUR5M [...] from February 2017 to December 2020 with our share of that income having enabled us to employ 10-12 staff and additionally 8-10 interns on 6 month contracts*" **[C7]**.

The incorporation of ISRU into ESA policy has led to several new jobs in Europe as confirmed by the ESA LRLTL:

> "*Thanks to this momentum, ESA could also start to gather a group of experts and researchers in its centers of ESTEC (The Netherlands), ECSAT (UK) and EAC (Germany) on ISRU*" **[C1]**.

C. Impact on Understanding, Learning and Participation

One of the most important aspects of any research programme is the impact it can make through inspiration of school students, acknowledging that they are our next generation of scientists and engineers. Impact comes from provision of resources to schools to enhance science education - but is greatly increased if teachers have confidence in their own skills and knowledge in teaching the material. We have an active Outreach and Engagement Programme and have used the vision of sustainable exploration enabled by lunar science and ISRU to engage a variety of audiences, especially school students, in a greater awareness of the importance and excitement of space exploration.

One specific example is our 'Living on the Moon' project which is a progression from the exhibition we designed and ran for the highly-competitive Royal Society Summer Exhibition in July 2019 (and which we were invited to reprise on-line in summer 2020). In partnership with The Ogden Trust and the South East Physics Network (SEPnet) we have developed a multi-interventional educational and outreach programme for school students. A central component of the programme is a continuing professional development element for teachers. In November 2020, we ran a pilot at a local primary school. We engaged with 3 teachers and 3 teaching assistants along with 79 pupils from years 5 and 6 over a period of 3 weeks.

The partner school was rated by OFSTED as 'requiring improvements' with only 2% of its KS2 pupils achieving at a higher standard in reading, writing and mathematics compared with the national average of 11%. A significant proportion of the pupils are underprivileged, with 20% eligible for free school meals.

Evaluation comprised comparison of pre- and post-intervention data and showed an increase in knowledge about the Moon among the pupils and an increase in the number of students discussing lunar research with their families. In particular, feedback from teachers suggested marked changes in pupils' aspirations, engagement, and awareness of STEM careers and of what is possible by studying science and mathematics.

Teachers' feedback included **[C8**, pp.1-2**]**:

> *"The very fact that you provided resources for the experiments […] ensured that we have actually done those practical experiments. We've learnt a lot*" (p.1).
>
> "*because we were talking to people [*who were experts in their field*] […] that's really enabled [our children] to understand the jobs that people do within science beyond just learning lessons in school, which has been really inspiring"* (p.1).
>
> *"I had a limited knowledge, but you don't realise how much your own knowledge grows […] When the children had talked about it afterwards […] I've been able to really scaffold that because my own knowledge has grown and I feel that has brought the children's confidence on because I have been able to help them make more sense of it [...]. I think my class got the most because our children come from different backgrounds. The children that we teach need to have that aspiration within themselves to believe that they can do what they want to do".*

5. Sources to corroborate the impact

C1. ESA testimonial on impact on policy development & implementation for lunar exploration.
C2. Testimonial from ESSC on **Anand's** role in reviewing ESA's E3P programme.
C3. UK Space Agency testimony of impact on UK's policy toward lunar exploration projects.
C4. Leonardo testimony on impact leading to EUR31,500,000 and 8,400,000 contracts.
C5. UK SME Fluid Gravity Engineering letter on new market, services, income, positioning.
C6. UK SME Dynamic Imaging Analytics testimony on new products, market, growth.
C7. Belgian SME Space Applications Services BV testimony on new business line, services.
C8. Teachers' feedback after participating in 'Living on the Moon' primary school project.