Space Resources – From the Moon to Near-Earth Asteroids and Back

Dennis Harries[1]

[1]*European Space Resource Innovation Centre (ESRIC), Luxembourg Institute of Science and Technology/Luxembourg Space Agency. 41, rue du Brill, 4422 Belvaux, Luxembourg (dennis.harries@esric.lu)*

Space exploration is a frontier that challenges creative and sustainable use of extraterrestrial materials. Whilst space missions during the past decades entirely relied upon supplies brought from Earth, future missions aiming at long-term human and robotic activity outside of Earth's atmosphere require technologies to produce propellants, life support, and construction materials from local extraterrestrial resources. This in-situ space resource utilization (ISRU) is key for the exploration of the Moon and Mars and to make space transportation more economical and environmentally sustainable. Examples are in-orbit fuelling and refuelling of spacecrafts, as well as the resource-efficient and circular processing of materials for building habitats and photovoltaic energy infrastructures.

The Moon's south polar region will a primary target for long term exploration starting with the international Artemis missions led by NASA. This area is particularly interesting due to its permanently shadowed regions (PSRs) inside polar craters, which are expected to hold water ice and other volatiles trapped by the very cold temperatures within. Remote sensing and the impact experiment of NASA's LCROSS mission places constraints on the amount and composition of volatiles, confirming the presence of water ice at several volume percent of the regolith [1]. Hydrogen gas produced from PSR ices or imported from Earth is the basis of oxygen generation from lunar ilmenite through redox reaction ($FeTiO_3 + H_2$ -> $Fe + TiO_2 + H_2O$) and electrolysis of the produced water. Alternative to this is the electrolysis of lunar regolith itself in the FFC Cambridge process employing a molten calcium chloride electrolyte. The FFC process reduced not only ferrous oxides but almost the entire oxide components of the regolith to produce a high yield of oxygen. Both processes require volatiles (hydrogen, chlorine) that need to be efficiently recycled due to their limited abundance on the lunar surface.

Carbon and nitrogen compounds such as CO_2 and NH_3 are present in PSRs, but their overall abundance is uncertain and in case of CO_2 suitable traps may be rare [2]. With typical carbon and nitrogen concentration of 10s to a few 100s of ppm in the average lunar regolith, mainly through solar wind implantation, both elements are geochemically highly limited but, besides hydrogen, essential for life support and most propellants. For propellants a sustainable circularisation of volatiles is obviously not possible.

Ryugu and its potential near-Earth asteroid (NEA) siblings are now confirmed to contain up to ~6.8 wt% H_2O [3] chemically bound in serpentines and smectites. Up to ~4.6 wt% of carbon are present as carbonates and organic matter that also contains considerable amounts of nitrogen. As discussed above, hydrogen, carbon, and nitrogen are critical resources for extended lunar presence and chemical manufacturing of propellants in space. As carbon and nitrogen are especially limited on the lunar surface, the retrieval of such resources from NEAs might become a long-term option for a sustained space economy. These asteroids are comparably easy to reach with low Δv requirements from and into cis-lunar space [4]. Exploratory heating experiments of C-type chondritic meteorites using high-vacuum extraction and mass-spectrometric detection of released volatiles indicated complex release patterns of H_2O, CO_2, CO and nitrogen compounds (Fig. 1). Thermodynamically valuable CO appears to be a major species and likely the result of redox reactions involving the carbonates, organic matter and magnetite. Extraction yields, energy requirements, and catalytic chemical conversion of this potential feedstock into further products, such as fuels and oxidizers, are some of the to-be-studied process constraints for NEA-based ISRU. Operating on small, nearly cohesionless rubble-pile asteroids is another extreme challenge for both small body exploration and any future ISRU.

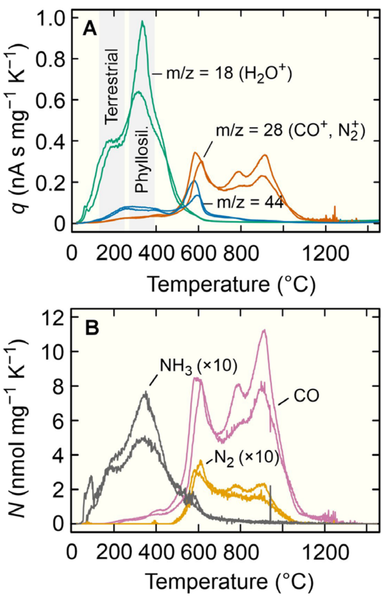

Figure 1: Volatile species detected by quadrupole mass spectrometry during controlled high-vacuum heating of the Murchison CM2 chondrite at 10 K/min. A. normalized ion currents. B. Species after fragment pattern deconvolution.

References

[1] Colaprete A. et al. 2010. Science 330:463–468. [2] Schorghofer N. et al. 2021. Geophysical Research Letters 48:e2021GL095533. [3] Yokoyama T. et al. 2022. Science eabn7850. [4] Jedicke R. et al. 2018. Planetary and Space Science 159:28–42.