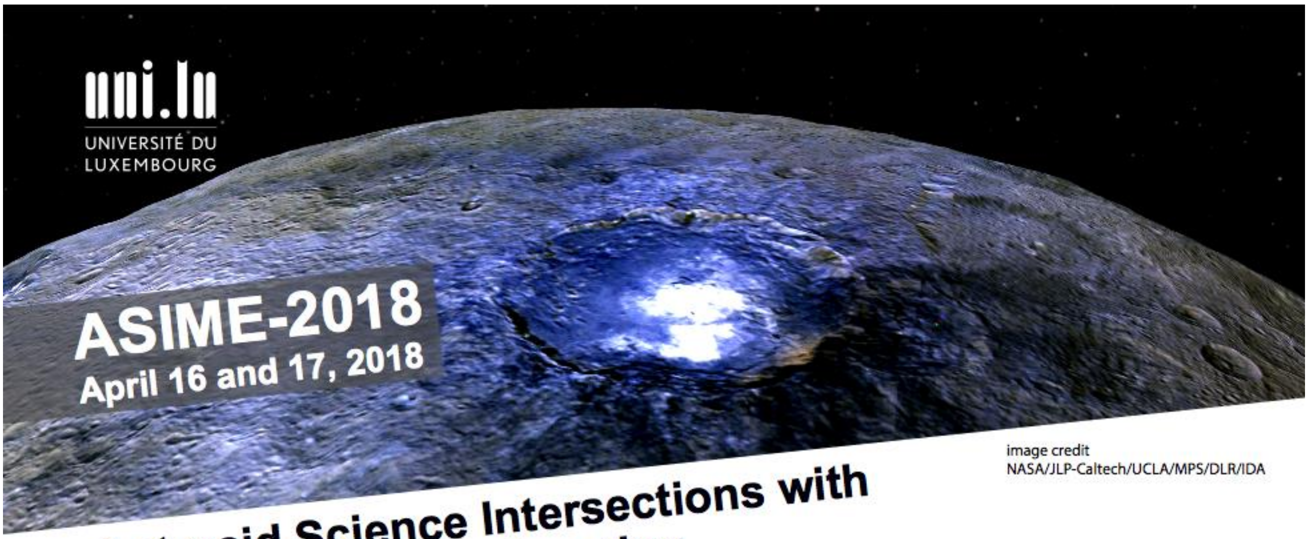


Asteroid Science Intersections with In-Space Mine Engineering

Abstracts

With Special Thanks to our Sponsors:

LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY LIST

uni.lu UNIVERSITÉ DU LUXEMBOURG

europlanet

Fonds National de la Recherche Luxembourg

THE GOVERNMENT OF THE GRAND DUCHY OF LUXEMBOURG
Ministry of the Economy

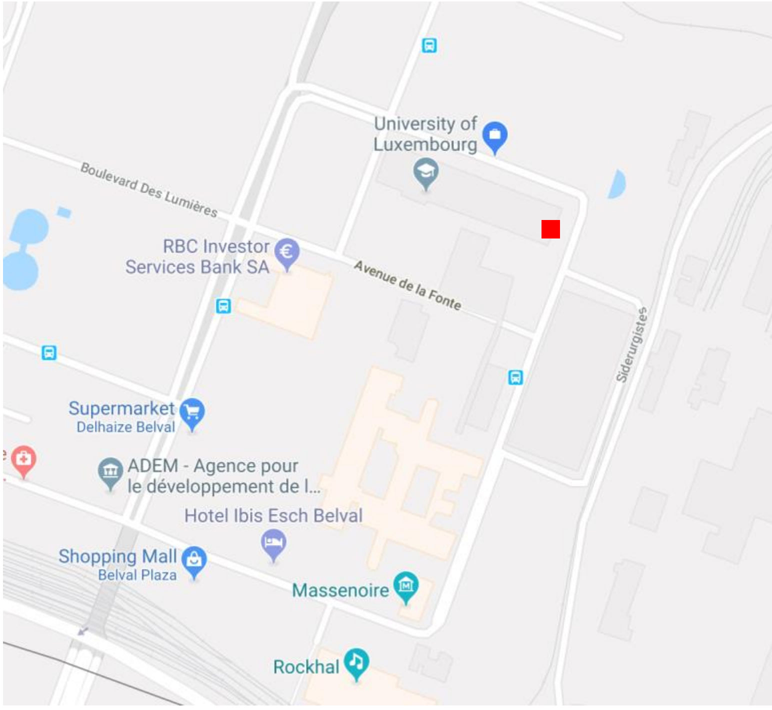
SPACE RESOURCES.LU

Practical Information:

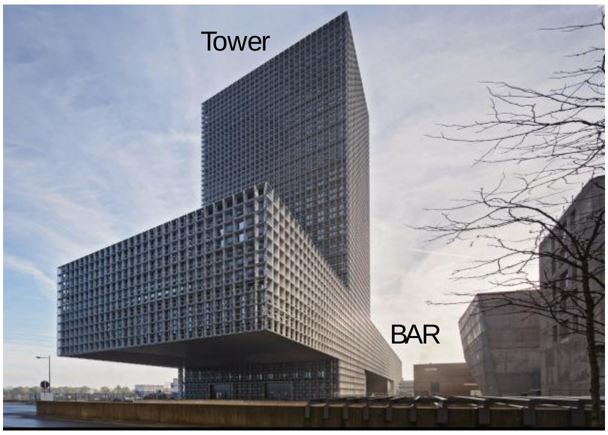
ASIME will be held in Maison du Savoir (MS), Room 3330

Signs will be posted to help you find the room.

Here is a map showing the location of the Ibis near the bottom of the map. And the red square shows the approximate location of the room in the MS.



The MS is the big tall black building. The meeting will be held in the BAR (the long part of the MS) opposite end of the tower. You can ask anyone to tell you where the MS is.



Program

16-April, 2018

8:00 Registration opens. Coffee/Tea/Refreshments

8:30 ASIME 2018 Introductory Remarks

- *Tonie Van Dam and Amara Graps*

8:40 Questions from the Asteroid Mining companies

- *Patrick Michel and Amara Graps* presentation of the Scientific Questions regarding Asteroid Composition as provided by industry: *Deep Space Industries, Planetary Resources, TransAstra, Aten Engineering, SolSys Mining, ispace*

9:30 Break for the arrival of the Dignitaries

9:40 Official Opening

- *Etienne Schneider*, Deputy Prime Minister and Minister of the Economy, The Government of Grand Duchy of Luxembourg
- *Yves Elsen,* Chairman of the Board of Governors of the University of Luxembourg
- *Marc Schiltz,* Executive Head of the Fonds National de le Recherche (FNR)
- *Patrick Michel, Scientific Overview of ASIME 2018*

10:00 Coffee Break

10:20 Session I: Composition from Spectroscopic Observations from the Ground

- **10:20 Keynote:** Ground---based spectroscopy in the visible and near infrared to extract mineralogical composition of asteroids, *Julia de Leon et al.*
- **11:20** Real Life Testing of a Novel Astronomical Prospecting Technique, *Martin Elvis, Anthony Taylor, Anthony Stark and Peter Vereš*
- **11:40** Simulating asteroid materials with realistic compositions, *Dan Britt and Kevin Cannon*

12:00Intro/ Status / Pitches: Industry asteroid mining activities, *Planetary Resources, Deep Space Industries, TransAstra, Aten Engineering, SolSys Mining*

12:45 Lunch

13:45 Session II: Composition from Spectroscopic Observations from the Ground (Continued)

- **13:45 Keynote:** Overview of the Asteroid composition: Spitzer Rosetta Lutetia flyby results with spectral limitations, *Antonella Barucci Observatoire*
- **14:15 Keynote:** Asteroid composition: Compositional Diversity Among Primitive Asteroids, *Humberto Campins*

- **14:45 Keynote:** Asteroid composition: How Many Hydrated NEOs Do We Expect? *Andy Rivkin and F. E. DeMeo*

15:15 Coffee Break

- **15:35** Technology and Asteroid Science Working Together for the Successful Development of Asteroid Resources, Angel Abbud-Madrid and Christopher Dreyer
- 15:55 Computational considerations for 3D full-wave asteroid Tomography*, Sampsa Pursiainen and Mika Takala*

16:15 Session III. Lunar and other Space Resources

- **16:15 Keynote:** The Moon's Role in the Development of Space Resources, *Ian Crawford*
- **16:45** LIST Applications and Activities for Space Resource Utilisation, *Tom Wirtz*
- **16:55** ispace's Approach to Lunar Resources Exploration, *Abigail Calzada-Diaz, Kyle Acierno, and Philippe Ludivig*

17:05 Round Table Discussion: *Alan Fitzsimmons*

19:00 Buffet Dinner

19:15 Search for Life*, Pete Worden*

17-April, 2018

8:00 Coffee and Refreshments

8:30 Session IV: Asteroid Composition from Lab measurements

- **8:30 Keynote:** Heating processes in primitive asteroids as revealed by the study of organics and hydration of CMs and ungrouped C1/2 chondrites, *Lydie Bonal*
- **8:50 Keynote:** Quantifying hydration from IR signatures of primitive meteorites**,** Pierre Beck
- **9:20** Analogue Materials Measured Under Simulated Asteroid Conditions: Insights into the Interpretation of Thermal Infrared Remote Sensing Observations, *Kerri L. Donaldson-Hanna et al*
- **9:40** In-situ spectra from Chang'E-3 and laboratory spectra of meteorites, *Wu Yunzhao*

10:00 Coffee Break

10:20 Session V. Composition from Taxonomy with Dynamics

- **10:20** A Novel Asteroid Taxonomy with 3D Photometric Colors based on Spectroscopy, *H.-K. Moon et al.*

- **10:40 Keynote:** The composition of asteroids from sky surveys, *Benoît Carry*

11:10 Session VI. Composition from Space Missions

- **11:10 Keynote**: NEOWise, *Amy Mainzer*
- **11:40 Keynote***: Japanese Second Sample Return Mission: Hayabusa 2, Tomoki Nakamura*

12:10 Lunch

13:40 Session VI. Composition from Space Missions (Continued)

- **13:40 Keynote**: Hera mission relevance for asteroid resource exploitation, *Michael Küppers*, *Ian Carnelli,Patrick Michel*
- **14:20 Keynote:** Results of the Dawn Mission to Vesta and Ceres, *Carol Raymond*
- **14:50** Possible Space Resources and Potential Applications in Future, *Lin Yangting*

15:10 Coffee Break

15:30 Session VI. Composition from Space Missions (Continued)

- **15:30** Efficient Massively Parallel Prospection for ISRU by Multiple Near---Earth Asteroid Rendezvous using Near-Term Solar Sails and 'Now-Term' Small Spacecraft Solutions, *Grundmann et al* (30 co-authors)
- **15:50** Extensive exploration of small bodies with autonomous navigation. BIRDY, *M. Agnan, D. Hestroffer, et al.*

16:10 Wrap Up:

- How to Improve Our Knowledge of Asteroid Composition, *Simon Green*
- Q & A
- White Paper/Journal Article Discussion

18:00 Buffet Dinner

Questions About Asteroid Composition

Dear Asteroid Scientists,

The following questions (in Google Docs form: https://goo.gl/eb7F5A) are the current questions from the asteroid mining industry that drive the content of this ASIME 2018 meeting. This meeting focuses on asteroid composition. We have the 2016 answers to many of these questions. For this meeting, we will discuss these questions as we ready the white paper.

(Questions and replies from ASIME 2016 can be found in the white paper from that workshop that can be found here https://arxiv.org/abs/1612.00709)

Asteroid Survey: Questions to define a mission…

1. [revisit] What instrumentation should an exploration probe carry in order to establish with 100% confidence that water and/or hydrated minerals are present on an asteroid, and what further instrumentation, if any, would be required to ascertain how much water there is?
2. [revisit] How can the rate of spectral characterisation of NEOs be increased? It lags far behind discovery rate, especially at smaller sizes (D < 300m).
3. While low-to-medium resolution spectroscopy in the 0.4 - 4.0 micron range is the best way to obtain a taxonomic classification of an asteroid, is it possible to obtain similar results using colour photometry?
4. *Technically*, and *scientifically*, how does spectroscopy of an asteroid at short (km range) distances differ from spectroscopy with ground-based telescopes?
5. [revisit] How can the water absorption feature at 3.1μm be best used as an indicator of hydrated minerals on carbonaceous asteroids? What additional measurement would further increase the quality or fidelity of the measurement?
6. [revisit] What conditions would permit the presence of free water ice on an NEO (e.g., on an extinct comet), and what would be the best way to detect it remotely?
7. [revisit] How could neutron detection support prospecting activities, and what is the maximum depth at which a neutron detector could detect the presence of water?
8. What instrumentation should an exploration probe carry in order to establish with 100% confidence that water and/or hydrated minerals are present on an asteroid, and what further instrumentation, if any, would be required to ascertain how much water there is?
9. [revisit] Is there any evidence that the shape of an asteroid provides information on its composition?
10. [revisit] Is there any evidence that the orbit of an asteroid provides information on its composition?
11. [revisit] What highest value telescopic composition/characterisation studies

are not being pursued for lack of funding or perceived low priority from space agencies?

12. [revisit] What observable phenomenon can help constrain the potential presence of resources from ballistic experiments such a Hayabusa-II's SCI (Small Carry-on Impactor) experiment?

Asteroid Surface Environment

These questions deal with detection methods that are at the surface or near-surface, say 1 meter down. This session would cover asteroid: regolith, polarimetry, neutron, gamma ray spectroscopy, radar, and thermal inertia studies, space weathering, asteroid-meteorite laboratory links, electrostatic studies, shape modelers (photometry or radar could be considered 'subsurface too).

13. [revisit] Can regolith simulants be developed that are similar enough to the real thing that experiments would provide accurate results useful to define engineering requirements?
14. [revisit] Could we develop asteroid material simulants based on meteorites; how well do meteorites represent the NEO population, especially at larger (D > 10m) sizes?
15. [revisit] How well understood are the processes of space weathering, and can we tell what the original state of the surface was, based on the current state?
16. [revisit] What signatures of past water of hydrated minerals could be observed on an asteroid surface that might indicate subsurface water or hydrated minerals?
17. [revisit] How can the surface desiccation of carbonaceous asteroids be determined (via remote observation, in situ measurements, or theoretical models) as a function of MBA to NEO transport lifecycle?
18. [revisit] What proximity observations and measurements would better link remote observations to meteorite studies.
19. Is anyone working on software that combines various meteorite spectra in an attempt to reproduce an asteroid spectrum that might contain contributions from two or more surface compositions?

20. [revisit] What physical and chemical complications are known, and what needs further research, in the thermal process considerations for extraction of water from carbonaceous asteroid material?

21. [revisit] Among the scientific community, what is the current confidence that spectral class informs bulk composition, given space weather and the results from recent missions connecting asteroids with certain spectral classes to known meteorite types?

22. What is the state of the art regarding matching meteorite spectra to asteroid spectra, and matching artificially weathered meteorite spectra to asteroid spectra?

23. Is anyone working on software that models how weathering affects meteorite spectra, to then attempt to match asteroid spectra to this modelled weathered meteorite spectra?

Asteroid Subsurface Environment

Question(s) in this category are concerned with the asteroid subsurface, i.e. an asteroid's interior properties. These questions include thermal modelling, rubble and pile cohesive strength studies, collisional disruption, penetrator instruments/methods, porosity studies, quantity of water and volatiles --which ties into Nice dynamical studies for asteroid formation location.

24. [revisit] Processing of mined materials will depend on composition and structure of the asteroid, and is a matter for engineering; is it necessary to develop these methods in the near future or can development be postponed until the asteroid mining industry is more mature?

Abstracts

Ground---based Spectroscopy in the Visible and Near Infrared to Extract Mineralogical Composition of Asteroids

Julia de León[1,2], Noemí Pinilla---Alonso[3], Humberto Campins[4], Javier Licandro[1,2], David Morate[1,2]

[1]Instituto de AstroSsica de Canarias --- IAC, Tenerife, Spain, [2]Departamento de AstroSsica, Universidad de La Laguna, Tenerife, Spain, [3]Florida Space Institute, University of Central Florida, Orlando, FL, USA, University of Central Florida, Orlando, FL, USA

Remote sensing remains the primary method to study the asteroid composition: ground- based spectroscopy and photometry in the visible and near-infrared wavelengths are the main techniques to determine the presence of different mineral species. The light from the Sun interacts with such minerals and diagnos1c absorption bands appear in the visible and the near-infrared spectra of the observed objects. In addition, measurements of several spectral parameters like the slope, the wavelength position of the center of the absorption bands, as well as their depth, and the ratio of their areas, provide us with valuable information like the relative end member abundances (weight percentage) and compositions in mineral mixtures, the grain size, or the effects of space weathering. Among the most interesting compounds that can be identified in the surface of asteroids are those found in primitive objects: carbon and organic compounds, as well as minerals that have been altered by the presence of liquid water. We present an overview on the compositional information that can be extracted from visible to infrared spectra of asteroids, as well as the latest results of our spectral characterization of the collisional families of primitive asteroids located in the inner belt (PRIMASS), and considered the most likely source of primitive near-Earth asteroids.

Real Life Testing of a Novel Astronomical Prospecting Technique

Martin Elvis*, Anthony Taylor, Anthony Stark and Peter Vereš

Harvard-Smithsonian Center for Astrophysics) Harvard-Smithsonian Center for Astrophysics, 60 Garden St., ms.6, Cambridge MA 02138 USA
Phone: +1 617 495-7442 ; fax: +1 617 495-7356 http://cfa.harvard.edu/~elvis

In principle using astronomical telescopes and techniques can cut the risk and cost of prospecting for ore-bearing asteroids by as much as 90%. In practice this is not happening with current science- and planetary defense oriented programs. We have been testing a novel approach that solves the two primary problems with a single telescope and instrument combination. The two problems are: (1) having a good enough orbit that each asteroid can be confidently recovered on its next apparition; (2) obtaining accurate colors for the asteroid to know what its surface rock is made of.

The PISCO imager (PI: Stark) is unique in having both a wide field of view and small pixels, and simultaneous 4-band imaging. The first enables us to use the extremely accurate (~10mas) star positions from the ESA Gaia satellite; the latter gives us colors that are unaffected by asteroid rotation. By using PISCO on the large (6.5 meter) Magellan telescope in Chile, we get robust, high signal-to-noise, data within 1

- 2 minutes. First results are very promising. We present these and show how we could scale this program to the level to support asteroid mining.

Simulating asterioid materials with realistic compositions

Daniel T. Britt [1,2] and Kevin M. Cannon*[1,2]

[1]Department of Physics, University of Central Florida, Orlando, FL 32816
[2]Center for Lunar and Asteroid Surface Science (CLASS), Orlando, FL 32816

Effective prospecting and mining of volatile-rich asteroids will require practical knowledge of the mineralogy and physical properties of asteroidal materials, and how these properties have evolved from accretion to the present. We have been working on a campaign to create high fidelity simulated planetary materials – simulants – in order to address strategic knowledge gaps in these areas. To date, we have designed and created four different carbonaceous regolith simulants based on the mineralogy of CI, CM, CR and C2 ungrouped chondrites; two Phobos simulants; and a Mars simulant. For C-type materials, the simulants are designed to match the modal mineralogy of a given meteorite class, or a specific representative meteorite (e.g., Orgueil). Minerals are sourced in industrial quantities, ground and sieved, then mixed together with water and cast into solid cobbles. The strength of these cobbles is mostly determined by the amount and type of serpentines and smectites present, which act as binders when the wet mixes have dried. To create "regolith", with a power law particle size distribution, the solid cobbles are ground in a rock crusher. We are currently working to measure the physical, spectral, and thermophysical properties of both the cobbles and regolith, which will be important for remote sensing studies and developing hardware to interact with volatile-rich asteroid surfaces.

In a related line of work, we have begun experiments to simulate ice melting and aqueous alteration of fine-grained matrices of carbonaceous precursor mineralogies. Parent bodies of carbonaceous chondrites accreted mixtures of submicron refractory minerals (matrix), ices, and chondrules. When the ice melted, the matrix silicates likely formed colloidal dispersions, or muds, that could have undergone large-scale convection. The evolution of these materials is key to understanding how much water has been sequestered and retained in the interior of C-type asteroids. We are beginning a series of experiments to: (1) re-create submicron mixtures of refractory minerals, (2) form colloidal dispersions from these mixtures at varying water:rock ratios, and (3) heat these materials to modest temperatures (50-150 °C) to study hydration reactions. The physical properties and reaction pathways of these matrix simulants can feed into thermal models of carbonaceous parent body evolution. This will help determine which asteroid spectral classes are likely to have the most preserved volatiles in their bulk interiors, regardless of the strength of the 3 micron band at the optical surface.

Aten Engineering

Aten Engineering is the first asteroid exploration and prospecting company in the world. We will map the asteroid resources in near Earth space, using telescopic as well as in-situ data, to provide current and future asteroid miners, as well as financial

investors, with all the information they need to make actionable decisions. It is of strategic importance to us to understand how observed asteroid spectra correlate with composi3on, and what are the most efficient, cost-effective means of obtaining these data.
Mining Near Earth Asteroids (NEAs) will not happen before appropriate exploration and prospecting has taken place. This is important to retire risk from a scientific, engineering and profitability perspective, which will in turn help assuage any hesitation investors might have. The distinct phases of asteroid prospecting, as we see them, are:

Phase 1: Discovery
Some 2,000 NEAs are discovered every year, and over 18,000 NEAs have been discovered so far, ranging in size from ~2 m to 34 km. The motivation is Planetary Defense, as NASA has been mandated by the US Congress to discover 90% of NEAs larger than 140m by 2020. Over 95% of NEAs are discovered by NASA-funded surveys.

Phase 2: Follow-Up
Follow-up astrometric observations of recently discovered NEAs are performed to improve the accuracy of their orbits to determine their probability of impact with Earth. The vast majority of NEAs pose no threat of impact and thus there is no incentive to improve their orbit accuracy any further. Other types of follow-up observations include photometry (to measure variations in brightness that may reveal the asteroid's spin period; lightcurves from multiple points around the asteroid's orbit can provide a shape model for it), multiband photometry (to measure differences in brightness in different discrete pass bands that reveal something about the asteroid's surface reflectance characteristics, and possibly composition), spectroscopy (to measure how the asteroid reflects the Sun's light, which may reveal its surface composition), and radar (which provides shape, size and spin characteristics, and sometimes surface characteristics). These observations are performed mostly for scientific purposes. There is currently a project at Lowell Observatory, MANOS, that is performing astrometry, photometry and spectroscopy of newly discovered low delta-v NEAs; their data will eventually be publicly released. Galache et al (2015) determined that rapid follow-up of new NEAs is of paramount importance to their characterization given how quickly they fade and become too dim to observe.

Phase 3: Data analysis
The various different types of asteroid observations provide data (orbits, spin periods, sizes, albedos, spectral taxonomy, etc) that are stored separately in uniquely formatted files, located in various locations. These data must be collected and collated, assembled into a single database, and analysed for the purposes of asteroid resource exploration. It is of particular interest to determine which of these asteroids are most accessible (have a low delta---v < 5kms, meaning the energy required to reach them is within the limits of current spacecraft capabilities), and of those, which have been classified taxonomically (so their likely surface composition has been inferred), and of those, which have an accurate enough orbit that a spacecraft could be sent to them. Finally, which of these is likely to contain the resource we are interested in?

Phase 4: In-Situ Exploration and Prospecting
Once the most likely candidates to bear the desired resources have been identified, the composition must be verified. This must be done via proximity measurements

because as Binzel et al (2015) have pointed out, remote observations do not provide reliable composi3onal information. While most information about an asteroid can be gained from an orbiting probe, a large fraction can also be acquired via the flyby of an asteroid, which has the advantage of allowing a single probe to visit several asteroids. To fully ascertain the presence of a particular resource and in what concentration it is available in, it is likely necessary to touch down on the asteroid and perform chemical analyses. It is certainly necessary to touch down in order to perform tests to determine the physical properties of the surface regolith, which is required so as to design mining equipment to the appropriate standard.

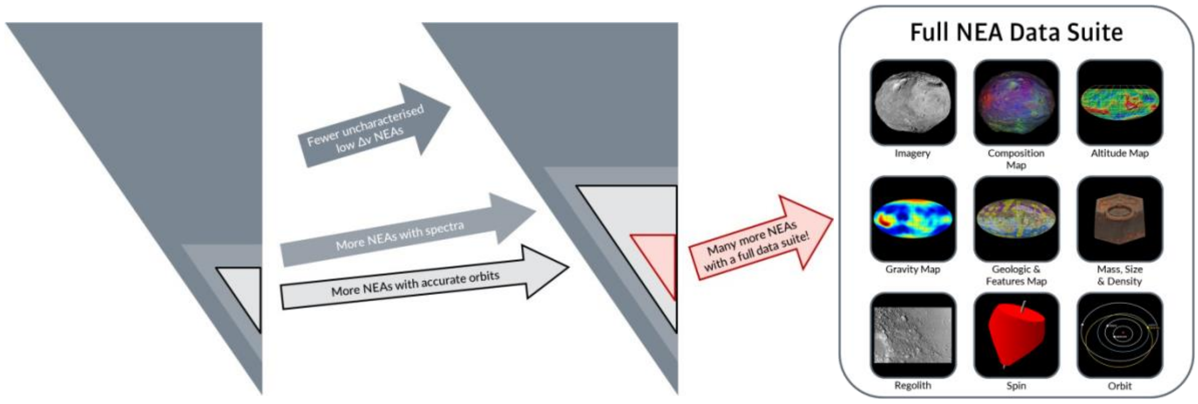


Figure 1: Aten Engineering's value proposition: Increase the number of fully characterized NEAs to allow for informed mining decisions to be made. A *Full Data Suite* can only be obtained through local observa3ons by an interplanetary probe. Dark grey triangles symbolize the amount of NEAs with low delta---v (less than 5 km/s); medium grey those that also have a taxonomy based on spectra collected from Earth; light grey those that also have an accurate orbit.

Based on current estimates of population numbers of 10m+ NEAs (~3.5 million, Trilling et al 2017; ~30 million, Harris & D'Abramo 2015), there are somewhere between 3,000 and 20,000 accessible, water‐rich NEAs. None of them will be mined without explora3on and prospecting activities to ascertain their value and mineability; that is Aten Engineering's mission.

References

Binzel, R. P., Reddy, V., Dunn, T. L., 2015. *The Near‐Earth Object Popula8on: Connec8ons to Comets, Main‐Belt Asteroids, and Meteorites*. Asteroids IV, pp. 243–256.

Galache, J. L., Beeson, C. L., McLeod, K. K., Elvis, M., 2015. *The need for speed in Near‐Earth Asteroid characteriza8on*. Planetary and Space Science 111, 155–166.

Harris, A. W., D'Abramo, G., Sep. 2015. *The popula8on of near‐Earth asteroids*. Icarus 257, 302–312.

Trilling, D. E., Valdes, F., Allen, L., James, D., Fuentes, C., Her‐rera, D., Axelrod, T., Rajagopal, J., Oct. 2017. *The Size Distribu8on of Near‐Earth Objects Larger Than 10 m*. AJ 154, 170.

SolSys Mining ‐ Investigating Solutions for in‐situ Regolith Benefication

Øystein Risan Borgersen

SolSys Mining AS, Oslo, Norway

The successful research and development of beneficiation and processing systems for space regolith is vital for utilization of in-space resources. Be it on asteroids, the Moon or Mars, systems which process regolith feedstock into specific concentrations and particle sizes remains an obstacle for in-space mining. While the in-space mining industry is attracting significant investment and attention, there has only been limited investment, research and development into regolith processing systems for in-space and Lunar operations. SolSys Mining AS aims to be the market leader in low/micro g and in-space beneficiation systems. With a multi-phase development approach, SolSys Mining is investigating the feasibility of in-situ regolith screening, sorting and comminution for the Moon and asteroids with its regolith beneficiation system. Working with leading companies in space and terrestrial mining, SolSys Mining is developing an initial concept study for its in-space processing equipment which will be levered to design and manufacture vital processing equipment to future space mining ventures.

Spitzer Rosetta Lutetia Flyby Results with Spectral Limitations

M. A. Barucci

LESIA – Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, Univ. Paris-Diderot, Sorbonne Paris Cité, France
Antonella.barucci@obspm.fr

The investigation of asteroids remains one of the major topics of planetary science. As primitive leftover building blocks of the solar system formation process, they offer clues to the chemical mixture from which the planets formed some 4.6 billion years ago and provide us information on some of the processes of the development of life on Earth.

Several asteroids were observed by space missions, but the major knowledge on asteroid composition is made, still today, by ground-based spectroscopy and analysed as taxonomic trend. The taxonomical classes have been defined and associated to meteorites, giving the asteroid mineralogy composition on the basis of meteoritic laboratory analysis. Nevertheless, about 2/3 of the mass of the asteroid belt seems absent from our meteorite collections, in particular for those taxonomical classes associated to the dark primitive objects, rich in volatiles and organics.

The spectral analysis of dark asteroids shows features indicating that liquid water was present on their surface during some previous epoch. About 60 % of the C- complex asteroids, at heliocentric distances between 2.5 and 3.5 AU, have undergone some kind of aqueous alteration process. Aqueous alteration is a low- temperature chemical alteration of compounds by liquid water which acts as a solvent and produces secondary minerals such as phyllosilicates, sulphates, oxides, carbonates, and hydroxides. Several transitions are only possible in the presence of liquid water on the surface of the object. Moreover, water ice and organics were observed on the surface of two asteroids of the C-complex, and recently on Ceres by DAWN mission. Systematic homogeneous analysis on large population of 600 primitive main belt asteroids, allowed to investigate the possible correlations between the aqueous alteration process and the asteroids taxonomic classes, orbital elements, heliocentric distances, albedo and sizes.

Interpreting surface compositions from asteroid spectra, despite the wide coverage in wavelengths, remains one of the biggest challenges. Many materials do not produce distinct, identifiable features in a reflectance spectrum. Moreover, the asteroid spectra are a result not only of composition, but also by grain size, temperature, viewing geometry, and space weathering processes.

The difficulty on the asteroid mineralogy understanding is also presented with the case of Lutetia, widely observed by ground spectroscopy, Spitzer and Rosetta mission.

Compositional Diversity Among Primitive Asteroids

H. Campins

University of Central Florida, Orlando, Florida, USA. campinsh@yahoo.com

Primitive asteroids are the most likely to contain hydrated minerals. Spectroscopic observations have revealed new and diagnostic differences among primitive asteroids. These asteroids show carbon-rich compounds, silicates with varying degrees of aqueous alteration and even surface ice; recent observations provide significant new constraints on their composition and other surface properties. Two sample-return missions, OSIRIS-REx and Hayabusa 2, will visit primitive near-Earth asteroids (NEAs). Most spacecraft-accessible NEAs originate in the inner asteroid belt, which contains several primitive asteroid families and a background of primitive asteroids outside these families. Initial results from these families offer a tantalizing preview of the properties expected in the NEAs they produce. So far, primitive asteroids in the inner belt fall into two spectral groups. The first group includes the Polana-Eulalia families, which show considerable spectral homogeneity in spite of their dynamical and collisional complexity. In contrast, the Erigone and Sulamitis families are spectrally diverse and most of their members show clear 0.7-µm hydration features. The two sample-return targets (101955) Bennu and (162173) Ryugu, most likely originated in the Polana family. An agreement between observations of inner-belt families (Pinilla-Alonso et al. 2017; Morate et al. 2018) and laboratory simulations of space weathering (Lantz et al. 2015 and 2017) has testable implications for Bennu and Ryugu: older terrains would be expected to be bluer than younger surfaces.

How Many Hydrated NEOs are There?

A.S. Rivkin[1] and and F. E. DeMeo[2]

[1]JHU/APL, andy.rivkin@jhuapl.edu)
[2]MIT

Hydrated minerals are tracers of early solar system history, and have been proposed as a possible focus for economic activity in space. Near-Earth objects (NEOs) are important to both of these, especially the most accessible members of that community. A variety of hydrated species have been observed on main-belt asteroids, but the hydrated minerals in meteorites are largely phyllosilicates or other hydroxides. The spectra of the most common hydrated meteorites, the CM

chondrites, are marked not only by an absorption feature near 3 µm caused by OH and H_2O, but by an associated absorption near 0.7 µm caused by oxidized iron. In common asteroid taxonomies, this latter absorption band is the defining feature of the Ch asteroid spectral class.

Because there are very few identified hydrated NEOs, we use the Ch class of asteroids as a proxy for hydrated asteroids, and use published work about NEO delivery, main-belt taxonomic distributions, NEO taxonomic distributions, and observed delta-v distributions to estimate the number of hydrated asteroids with different threshold sizes and at different levels of accessibility. We expect 25-100 Ch asteroids to be present in the known population of NEOs > 1 km diameter, with 5-18 of them more accessible on a round trip than the surface of the Moon. If there is no need to define a minimum size, we expect 280 to over 1000 hydrated objects that meet that accessibility criterion. While there are few unknown NEOs larger than 1 km, the population of smaller NEOs yet to be discovered can also be expected to contain proportionally-many hydrated objects.

We will present these findings, how we reached them, and what they do and do not imply about the population and transport of hydrated asteroids.

Technology and Asteroid Science Working Together for the Successful Development of Asteroid Resources

Angel Abbud---Madrid* and Christopher Dreyer

Colorado School of Mines, Golden, Colorado, 80401, United States

Several solar system airless bodies, including near-Earth objects, Main Belt asteroids, comets, and possibly the moons of Mars contain a variety of volatile compounds. These volatiles may be ices mixed with other solids, or they may be bound to hydrated minerals. Bodies with sufficient concentrations of volatile---bearing materials could one day become ore bodies; that is, technologically and economically viable sources of feedstock for in---space manufacturing of propellants and life-support consumables needed for the human and robotic exploration of space. Production of these commodities in space, using in situ raw materials, would also allow for the expansion of our economic sphere to include commercial activities in space to cut our dependence from the energy intensive and extremely costly launching of materials from Earth, which we have conducted since the dawn of the space age.

Thus, in conjunction with the much-needed scientific characterization of the physical properties and mineral composition of asteroids and other bodies, technology must also be developed to design systems to extract volatile compounds from these bodies and effectively separate the volatiles considered as valuable resources from other undesirable elements. Potential asteroid resources become proven resources only when the technologies and processes to convert them to useful products are understood. Recent experimental work conducted at Colorado School of Mines with materials representative of carbonaceous near-Earth asteroids show that some ore bodies will require simple heating to obtain valuable volatiles such as water and carbon dioxide, while others will require more complex processing and refining operations. These preliminary experimental studies form the basis for additional investigations needed to assess potential processes for extracting volatile compounds from solar system bodies. These investigations will then guide both the requirements for additional scientific data collection and the development of technologies for mineral extraction and production of in---space propellant and human consumables. In other words, technology and asteroid science must advance together for the successful development of asteroid resources.

Computational Considerations for 3D full-Wave Asteroid Tomography

Sampsa Pursiainen and Mika Takala

Laboratory of Mathematics, Tampere University of Technology, PO Box 692, FI-33101 Tampere, Finland, sampsa.pursiainen@tut.fi

This presentation will concentrate on computed radar tomography (CRT) of asteroids. CRT is used in geophysical imaging and surveys to find out the structure and composition of ground layers and glacier ice as well as to localize and detect water and mineral resources. Full-wave CRT is a computationally intensive imaging method which will potentially enable finding out the complete three-dimensional dielectric permittivity structure of a small asteroid via measurements performed by an orbiting spacecraft.

Characteristic to spaceborne CRT measurements is the need to invert far-field data, since steering a spacecraft into a stable orbit is a major challenge due to the low escape velocity of the target asteroid. I will introduce a mathematical far-field model and its numerical discretization developed for this purpose. Finding a 3D reconstruction via a multigrid-based inversion technique will be discussed. I will also present numerical examples on creating a realistic asteroid model and on how the CRT simulation for such a model can be run in a state-of-the-art computation cluster.

The Moon’s Role in the Development of Space Resources

Ian Crawford

Department of Earth and Planetary Sciences, Birkbeck College, University of London

There is growing interest in the possibility that the resource base of the Solar System might in future be used to supplement the economic resources of our own planet. As the Earth’s closest celestial neighbour, the Moon is sure to feature prominently in these developments. In this talk I will briefly review lunar resources and their possible applications, and discuss how lunar resources compare with asteroid resources. I will argue that lunar resources have both advantages and disadvantages compared to asteroids, depending on the nature of the resources and where they are to be used. Nevertheless, the Moon is likely to play a central role in the development of a space economy for the following reasons: (i) The Moon, unlike asteroids, is constantly close to the Earth; (ii) Lunar gravity may be an advantage for some extraction and manufacturing processes; (iii) Lunar geological processes have concentrated a number of useful materials that are not concentrated in asteroids; (iv) The Moon has been impacted by a wide variety of asteroids throughout its history, so the lunar surface may additionally prove to be a convenient depository of asteroidal resources; and (v) The lunar surface lends itself to supporting a diverse scientific and industrial infrastructure in a way that asteroid surfaces do not.

A Compact High Performance Magnetic Sector Mass Spectrometer for Space Applications

Tom Wirtz and Hung Quang Hoang

Advanced Instrumentation for Ion Nano-Analytics (AINA), Materials Research and Technology (MRT) Department, Luxembourg Institute of Science and Technology (LIST), 41 rue du Brill, L-4422 Belvaux, Luxembourg

Compact magnetic sector mass spectrometer instruments for space and planetary applications either utilise simple mass spectrometer configurations providing low performance [1, 2], or configurations leading to high performance but implying complex ion optical systems with serial mass spectral acquisition [3]. The Luxembourg Institute of Science and Technology has developed a high performance compact mass spectrometer based on the sector field type instrument that is capable of being used in space applications for the investigation of in-situ atmospheric, surface and subsurface chemical and isotopic compositions. The mass spectrometer is designed in such a way that it allows a wide mass range with parallel acquisition while keeping compact size and minimizing the complexity of the optics. The spectrometer design is based upon a double focusing magnetic sector spectrometer configuration, which consists of a spherical electric sector, a magnetic shunt and a permanent magnet sector. The magnetic sector is placed in an inclined angle with respect to the magnetic shunt in order to improve the focusing property of the analyser on the focal plane. The size of the mass spectrometer can be scaled for adapting it to different applications. For a spectrometer having a weight of less than 4 kg and fitting into a volume of 30x15x10 cm^3, the simultaneously detectable mass range (m_{max}/m_{min}) is about 40. Different sub mass ranges can also be optimized by shaping the exit plane of the magnetic sector into different planes to achieve the highest possible mass resolution. The mass resolution ($m/\Delta m$) of the spectrometer was experimentally demonstrated to be above 2000.

References

[1] D. Pullan, M.R. Sims, I.P. Wright, C.T. Pillinger & R. Trautner, “Beagle 2: the exobiological lander of mars express”, In Mars express: the scientific payload. ISBN 92-9092-556-6 (2004).
[2] R. Shotwell, “Phoenix—the first mars scout mission”, Acta astronautica 57, 121 (2005).
[3] H. Balsiger, K. Altwegg, P. Bochsler et al. “Rosina – Rosetta orbiter spectrometer for ion and neutral analysis”, Space science reviews 128, 745 (2007).

Ispace’s Approach to Lunar Resources Exploration

Abigail Calzada-Diaz[1], Kyle Acierno[1], and Philippe Ludivig [1,2]

[1]ispace Europe, c/o Paul Wurth InCub, Rue de l’Industrie 5, L-1811 Luxembourg
[2]Automation & Robotics Research Group, University of Luxembourg, Avenue de l'Université 2, 4365 Esch-sur-Alzette

ispace’s vision is to expand and sustain humanity's presence beyond Earth by utilizing resources available on the Moon. In order to accomplish this vision, ispace set a 3-step roadmap. The first step is the technology demonstration of ispace's rover as part of the Google Lunar XPRIZE. ispace, a finalist in the Grand Prize, developed and flight qualified the SORATO rover and won the $500K mobility milestone award. The second step is to build-upon the rover technology to perform missions that will prepare the establishment of in-situ resource utilization (ISRU) on the Moon. With proven technologies (Step 1) and a solid understanding of the lunar environment and distribution of resources (Step 2), ispace will be ready to execute the third step, the processing and utilization of lunar resources (Step 3). The company is headquartered in Tokyo, Japan and has its largest subsidiary in Luxembourg.

Today, ESA and NASA’s Space Exploration Strategies [1,2], as well as the Global Exploration Roadmap by the International Space Exploration Coordination Group [3], highlight the importance of the Moon and its development as the first stepping stone to achieve further and more complex exploration targets such as Mars or Asteroids. The lunar surface not only offers many opportunities for scientific research, it also contains abundant raw materials that will facilitate human activities and promote a cis-lunar economy. In contrast to near-Earth asteroids, where resources (specially iron, nickel, etc.) are of significant importance, the lunar surface has the capability to sport near-term scientific and industrial infrastructures thanks to its close proximity to Earth (only 4 days to travel there or 1.5 seconds to communicate), physical characteristics (larger gravity values than asteroids), and the economically important materials, such as water and other volatiles [4].

From all the available resources on the lunar surface, water ice is becoming the first ISRU target. Water is a key resource to be used as fuel, it is essential for life support systems in long-term lunar exploration missions (including drinkable water for astronauts) and it is required for most of the manufacturing processes that could take place in the Moon Village scenario [5].

With the support of the Government of Luxembourg, ispace Europe is developing the Polar Ice Explorer mission, the first public-private mission which will be the first project of Step 2. It is an ISRU exploration mission with the goal of identifying and define the extension of the hydrogen and potential water ice deposits in lunar polar regions. This mission also aims to help future ISRU mission by obtaining valuable information on the geotechnical and trafficability properties of the polar regolith.

Finally, ispace Europe is contributing to the development of key technologies for the lunar resource exploration through FNR-funded collaborations. ispace Europe is working together with the Luxembourg Institute of Science and Technology (LIST) in the creation of a new type of detector for magnetic mass spectrometers, and with the Automation & Robotics Research Group at University of Luxembourg in localization and navigation systems for space exploration rovers.

References:
[1] ESA. Exploring Together: The Global Exploration Strategy. 2015.
[2] NASA’s Plans for Human Exploration Beyond Low Earth Orbit. 2017.
[3] Space Exploration Roadmap, International Space Exploration Coordination Group, 2018.
[4] Crawford I.A. Lunar Resources: A review. Progress in Physical Geography. 2012.
[5] The Moon: Resources, Future Development, and SettlementSpringer. 2008.

Heating processes in Primitive Asteroids as Revealed by the Study of Organics and Hydra2on of CMs and Ungrouped C1/2 chondrites

Lydie Bonal, Pierre Beck, Eric Quirico, Bernard Schmitt
Institut de Planétologie et d'Astrophysique de Grenoble

Small bodies witnessed solar system formation and preserve a record of physical and chemical processes active around the young Sun. While often considered as primitive, many small bodies experienced geological processes including impacts, thermal metamorphism, and aqueous alteration. In particular, chondrites are exhumed from the interiors of their parent bodies by impacts, that may result in some heating and mechanical modification (compaction, deformation, fracturing, etc.).

Here I will report a combined Raman and infrared study of the composition and structure of insoluble organic matter and hydration state of a series of CM and ungrouped-C2 chondrites. I will show that these parameters are tracers of the extent and nature of thermal metamorphism a meteorite has experienced and reflect the degree to which the thermally driven and irreversible carbonization of IOM has proceeded. A few specific samples will be used to discuss in details the connection between parent body heating and impacts, as well as the presence of oxidation mechanisms during low temperature hydrothermalism.

These results could be used as a proxy for the analysis of the forthcoming samples from the HAYABUSA 2 and OSIRIS-REx missions, which will sample the subsurfaces of types C and B asteroids that likely contain a diversity of lithologies.

Quantifying Hydration from IR Signatures of Primitive Meteorites

Pierre Beck, Lydie Bonal, Eric Quirico, Bernard Schmitt

Institut de Planétologie et d'Astrophysique de Grenoble

Small bodies witnessed solar system formation and preserve a record of physical and chemical processes active around the young Sun. While often considered as primitive, many small bodies experienced geological processes including impacts (Beck et al., 2005; Gillet et al., 2007) thermal metamorphism (Bonal et al., 2016) and aqueous alteration (Krot et al., 2015). In the case of aqueous alteration, this process was experienced by all chondrites families (Brearley, 2006) but is most evident in meteorites belonging to the carbonaceous chondrites class, and particularly the members of the CI, CM and CR groups. The latter meteorite groups record a strong fluid/rock interaction leading to the sometimes-complete transformation of primary anhydrous silicates into phyllosilicates and oxides.

Visible-infrared spectroscopy remains the prime technique in order to search for the parent bodies of meteorites. This technique, whether applied in reflectance (typically in the range 0.35 to 4 µm) or in emission (typically 7---30 µm), has been used to decipher the mineralogy of solar system small bodies and their connection with known cosmomaterials. Signatures of aqueous alteration have been searched and found among the asteroid population. The strongest detected feature related to hydrous minerals is around 3-µm (Jones et al., 1990; Lebofsky et al., 1981; Rivkin et al., 2003;

Takir and Emery, 2012) and directly related to the presence of hydrogen (-OH stretching and H_2O bending overtone).

Here, I will focus on the IR signatures of hydration that can be detected in the VIS to MIR spectra of carbonaceous chondrites (0.35-150 µm). I will describe our effort to develop a quantification method based on laboratory measurements under asteroidal conditions. I will discuss the impact of vacuum, low-T and observation geometry on the hydration-related signatures.

Analogue Materials Measured under Simulated Asteroid Conditions: Insights into the Interpretation of Thermal Infrared Remote Sensing Observations

K. L. Donaldson Hanna, N. E. Bowles, H. C. Connolly Jr., V. E. Hamilton, L. P. Keller, D. S. Lauretta, L. F. Lim, and D. L. Schrader

Thermal infrared (TIR) emissivity measurements are sensitive to an airless body's near-surface (upper hundreds of microns) environment, porosity, and particle size resulting in challenges interpreting thermal infrared remote sensing observations of planetary surfaces. Thus, well-constrained laboratory TIR measurements of analogue samples for a range of particle sizes, porosities, and near-surface environments are needed. Near-surface conditions for a variety of Solar System bodies can be simulated using facilities within the University of Oxford's Planetary Spectroscopy Facility (PSF). Vacuum chambers within the PSF are capable of simulating such conditions, by varying the chamber's atmospheric pressure and temperature and the incident solar irradiation on the sample. By changing the near-surface environment, the thermal gradient in the upper hundreds of microns of the sample is varied, which can affect the position and contrast of diagnostic features in TIR spectra. The atmospheric pressure inside the chamber is varied between ~1000, ~5 and < 10^{-4} mbar to simulate Earth, Mars, and airless bodies (e.g., the Moon and asteroids) conditions. Adjusting the power of the solar-like halogen lamp until the brightness temperature of the sample is similar to the brightness temperature of the simulated planetary body simulates the solar irradiation on a planetary surface. Here we present laboratory emissivity spectra of a suite of fine particulate, well-characterized pure minerals and chondritic meteorites measured under simulated asteroid conditions. These well-controlled laboratory measurements enable the interpretation of remote sensing observations, which help in determining a planet's surface composition as well as the nature of its regolith.

In situ Spectra from Chang'E-3 and Laboratory Spectra of Meterorites

Yunzhao Wu

Key Laboratory of Planetary Sciences, Purple Mountain Observatory, Chinese Academy of Sciences; wu@pmo.ac.cn

Spectroscopy is an important tool for understanding the compositions of asteroids. To interpret their spectra acquired by telescope and spacecrafts, the measurements of the spectra of meteorites in the laboratory is widely performed. For the laboratory spectra measurements, one of the important aspects is the wide range of wavelength because the visible and near infrared spectroscopy (VNIR) is related to the transition metals and the middle infrared spectroscopy (MIR) is related to the molecular vibration or rotation. A second item needs to be paid attention to is that the laboratory environment and structural conditions are quite different from the pristine regolith on the surface of the asteroid. Based on the two reasons, I will show two researches: 1) the first *in situ* spectra of the airless body (the Moon) acquired by the Chang'E-3 Yutu rover; 2) the laboratory spectra of three distinct meteorites (NWA 10611which is eucrite, Seymchan which is pallasite, and Youxi which is mesosiderite) spanning from VNIR to MIR. The *in situ* spectra reveal that 1) the laboratory spectra are quite different from that of the true surface of the Moon and the uppermost soils are extremely space weathered; 2) the spectra of the uppermost soil detected by remote sensing exhibit substantial differences with that immediately beneath. It has important implications for the remote compositional analysis; 3) For the three meteorites, the VNIR and MIR spectra show that eucrite is rich in HCP, mesosiderite is rich in OPX and pallasite is rich in forsterite.

A Novel Asteroid Taxonomy with 3D Photometric Colors based on Spectroscopy

H.-K. Moon[1], D.-G. Roh[1], M.-S. Shin[1], Y.-J. Choi[1], T. Hiroi[2], and S. Sasaki[3]

[1]Korea Astronomy and Space Science Institute,
[2]Brown University
[3]Osaka University

We currently have ~2,500 asteroids with visible-near infrared (VIS-NIR) spectra since the 1970s. It was a dramatic shift that the Sloan Digital Sky Survey (SDSS) 4th Moving Object Catalog (MOC 4) was released with ~4×10^5 measurements of asteroid positions and colors in the early 2000s. A decade later, DeMeo and Carry (2013) made use of ~400 spectra to apply their taxonomy to ~1×10^5 MOC 4 asteroids. However, a large number of asteroids in their 2- dimensional parameter space (e.g., slope vs. i-z color) were seen as a continuous distribution of clouds of data points without distinct boundaries. Therefore, we introduce an improved system of asteroid taxonomy. This approach is simply represented by a triplet of SDSS colors. The centers of each taxonomic class are determined mathematically and the class boundaries are statistically established. We apply our scheme to MOC 4 calibrated with VIS- NIR reflectance spectra of DeMeo and Carry over plotted on convolved SDSS colors of laboratory meteorite samples. We successfully separate seven different taxonomy classifications: C, D, K, L, S, V, and X, with which we have a relatively sufficient number of spectroscopic datasets. In fact, color measurement is faster, simpler, and more cost-effective in terms of the time required, labor and cost for observation, data processing, and analysis. We note, however, that a coordinated effort on VIS-NIR spectroscopic surveys is essential for further improvement of this taxonomy where spectral data is used as control points. We expect our new scheme to make significant contributions in the era of the Large Synoptic Survey Telescope (LSST) and in-situ space utilization when we will see an increase of 10-100 times more objects in the solar system than currently known, thanks to next generation ground-based and space telescopes.

The Composition of Asteroids from Sky Surveys

Benoit Carry

Observatoire de la Cote d’Azur, Nice, France, benoit.carry@oca.eu

Dedicated surveys aiming at discovering and characterizing the orbits of small bodies successfully increased their sample to over 750,000 objects in the last decades, including over 17,000 near-Earth objects. However, little statistics was brought by the dedicated observations of their physical and compositional properties, which are crucial in both understanding the formation and evolution of the solar system and selecting targets for space missions.

The advent of electronic detectors and 4+m telescopes initiated spectroscopic surveys of asteroids in the visible in the 1990s, and in the near-infrared in the 2000s, leading to the definition of the currently used asteroid spectral classification. However, spectra were acquired for less than 10,000 asteroids in the visible and 3,000 in the near-infrared (crucial to disentangle several compositions). As such, the first truly statistical studies of small body were made possible by the extraction of small body signal from large astronomical surveys.

Over the last decade, the Sloan Digital Sky Survey (SDSS) and the NASA Wide Infrared Survey Explorer (WISE) were analyzed by dedicated pipelines, providing visible multi-filter photometry for 100,000 asteroids and diameters and albedo for 150,000. While broad-band multi-filter photometry cannot provide detailed mineralogical intelligence, it provides an efficient mean to sort asteroids into large compositional groups, allowing both statistical studies and productive target selection. The SDSS photometry allowed to study the distribution of asteroid taxonomy in the asteroid belt and near-Earth space, and guided many spectroscopic follow-up campaigns.

Currently operating ESA Gaia mission will release low-resolution visible spectroscopy for up to 300,000 asteroids in 2022, and the Large Synoptic Sky Survey (LSST) will release SDSS- like photometry for millions of asteroids between 2022 and 2032. In parallel, near-infrared colors for 40,000 asteroids were recently extracted from the VISTA Hemispheric Survey (VHS) and the ESA Euclid to be launched in 2022 is expected to provide near-infrared colors for 150,000 asteroids.

I will present how current and upcoming data can be used to (i) efficiently classify asteroids into broad taxonomic classes to study the compositional structure of the asteroid belt and its source regions of near-Earth asteroids, and (ii) select targets for productive spectral characterization.

Japanese Second Sample Return Mission: Hayabusa2

Tomoki Nakamura

Tohoku University, Japan: tomoki@m.tohoku.ac.jp)

Hayabusa2 mission was developed based on heritage of Hayabusa mission that realized first successful recovery of asteroidal sample to the Earth. Hayabusa2 spacecraft was launched in Nov 2014, carried our Earth swing by in Dec 2015, and will arrive C-type asteroid Ryugu around July this year. Ryugu is classified to C-type asteroids that are expected to contain hydrated minerals such as serpentine and organic material. Ground base observations of Ryugu suggested that the surface mineralogical distribution seems to be heterogeneous, but most regions show reflectance spectra similar to partially dehydrated carbonaceous chondrites, implying that Ryugu surface material experienced hydration and subsequent dehydration by heating (Vilas 2008; Sugita et al. 2013; Perna et al. 2017).

After arrival we will perform global mapping of Ryugu surface by using a visible telescope camera, a multiband visible to near infrared spectrometer, a near-infrared spectrometer, and a thermal infrared camera. Based on the results of the mapping, we will select several candidates for landing and sampling. The returned samples must maximize science return. We will perform first and second touch down before and after solar conjunction of 2018 winter, respectively. The collected samples will come back to the Earth 2020 winter. Six groups of different disciplines were selected and organized for initial analysis of the returned samples. The first results of Ryugu sample analysis will be shown in early 2021.

Hera Mission Relevance for Asteroid Resource Exploitation

Michael Küppers[1], Patrick Michel[2] and Ian Carnelli[3]

[1]ESA/ESAC, Spain
[2]Univ. Côte d'Azur, CNRS, Obs. Côte d'Azur, France;
[3]ESA HQ, France

ESA's Hera mission is part of the Asteroid Impact & Detection Assessment (AIDA) collaboration between NASA and ESA. NASA's DART mission will impact a projectile into the minor component of the binary near-Earth asteroid (65803) Didymos in 2022 (called "Didymoon"). The basic idea is to demonstrate the effect of the impact on the orbital period of the secondary around the primary. ESA's AIM will monitor the Didymos system for several months, allowing to evaluate the DART impact.
While the primary purpose of AIDA is the demonstration of asteroid detection, the measurements done by Hera do provide important data in preparation of asteroid mining. Hera is equipped with cameras, a lidar, and a cubesat carrying a visible and near-infrared imaging spectrometer. It will for the first time investigate an asteroid < 200m in size (Didymoon). Those very small asteroids are expected to be the first targets of the mining companies. The investigation of the physical properties of the surface layer (strength, roughness) as well of sub-surface properties (through observation of the interior of the DART crater) provides important information for the choice of mining techniques. Should an optional radar be added to the payload of Hera, the interior of both asteroids will be mapped as well.
Hera is one of the pathfinder missions that pave the way for asteroid resource utilisation.

Results of The Dawn Mission to Vesta and Ceres

C. A. Raymond[1], C. T. Russell[2] and the Dawn Science Team

[1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91001. Email: Carol.A.Raymond@jpl.nasa.gov,
[2]Institute of Geophysics and Planetary Physics, University of California, Los Angeles, 595 Charles Young Drive East, Los Angeles, CA 90095. Email: ctrussel@igpp.ucla.edu

The Dawn mission launched in 2007 on a history-making ion-propelled journey to visit the two most massive bodies in the main asteroid belt and learn about the conditions and processes that shaped the early solar system. Dawn explored Vesta for 14 months beginning in July 2011 using its framing camera (FC), visible-infrared spectrometer (0.4-5μm; VIR), gamma-ray and neutron detector (GRaND) and by mapping the topography and gravity. Dawn completed its comprehensive 16-month mapping of Ceres in June 2016, and has continued collecting data during its ongiong extended mission. The main results and implications of the investigations of these two bodies for the surface composition of these bodies are described below.

Dawn at Vesta**:** Prior to Dawn's arrival, much had been inferred about Vesta's evolution from study of the Howardite-Eucrite-Diogenite meteorites, for which Vesta was the presumed parent due to a match between the meteoritic spectra and that of Vesta from ground-based observations. The basaltic achondritic composition of the HED clan indicated that Vesta had undergone igneous differentiation, implying a (possibly global) magma ocean, formation of a large iron core, emplacement of basalts (eucrites) on the surface and cumulate gabbros (diogenites) at depth. Dawn confirmed the Vesta-HED connection via surface lithologic mapping using VIR spectra [1, 2] and elemental chemistry from GRaND [3, 4], that showed most of the vestan surface is composed of howardite-like material (a mixture of eucrite and diogenite), with localized enrichments of eucrite and diogenite. Unexpectedly, broad, dark regions shown to be hydrogen-rich by GRaND [3] and to exhibit an OH absorption feature at 2.8 μm in VIR spectra [5], are interpreted to result from a few % of exogenic CM carbonaceous chondrite mixed into the regolith [6, 7]. Dawn also found pitted terrains [8] in young craters interpreted to be the result of outgassing of volatile-rich material, and gullies [9] thought to result from transient flow of water, both associated with impact processes. The discovery of hydrated material on Vesta's surface implies delivery of volatiles to the inner solar system by primitive asteroids was an important process.

Dawn at Ceres: Prior to Dawn's arrival, Ceres was already known to be a dark, wet dwarf planet with evidence for altered minerals and water vapor emissions, from decades of ground- and space-based observations, and was thought to be at least partially differentiated. Dawn arrived at Ceres in March 2015 and found a heavily-cratered very dark surface that was punctuated by isolated, extremely bright areas [10]. In contradiction to pre-Dawn model predictions of an ice-rich, viscously-relaxed smooth surface, Ceres is shown to have a mechanically- strong crust and is gravitationally relaxed at long wavelengths, implying that the strong crust overlies a weaker deep interior [11, 12]. Compositionally, Ceres' surface is dominated by dark material, ammoniated Mg- phyllosilicates, and carbonates [13-15]. The ubiquitous presence of ammoniated material suggests formation in a cold environment, possibly in the outer solar system, while the overall mineralogy indicates Ceres' interior experienced pervasive alteration. Water ice has been observed in fresh craters at high latitudes, and elemental measurements indicate a shallow ice table [16]. These observations, along with Ceres gravity field [17] confirm that Ceres at least partially differentiated, providing evidence for an ancient subsurface ocean. Local morphology such as crater floor deposits, isolated mountains and the enigmatic bright areas indicate active processes on Ceres that likely involve brine-driven cryovolcanism [18]

References:
[1] De Sanctis M. C. *et al.* (2012), *MAPS, 48*.
[2] Ammannito E. *et al.* (2013), *MAPS, 48*.
[3] Prettyman T. H. *et al.* (2012), *Science, 338*.
[4] De Sanctis M. C. *et al.* (2012), *ApJ, 758*.
[5] Prettyman T. H. *et al.* (2013), *MAPS, 48*.
[6] McCord T. B. *et al.* (2012), *Nature, 291*.
[7] Reddy V. e*t al.* (2012), *Icarus, 221*.
[8] Denevi B. W. *et al.* (2012), *Science, 338*.
[9] Scully J.E.C. *et al.* (2015), *EPSL, 411*.
[10] Russell C. T. *et al.* (2016), *Science, 353*.
[11] Bland M. T. *et al.* (2016), *Nat Geo, 9.*
[12] Fu, R. R. *et al.* (2016), in prep for *EPSL.*
[13] De Sanctis, M.C. e*t al.* (2015), *Nature*, *528*.
[14] De Sanctis, M.C. e*t al.* (2015), *Nature*, *536*.
[15] Ammannito *et al.* (2016), *Science, 353*.
[16] Prettyman, T. H. *et al.*, *this meeting*.
[17] Park R. S. *et al*. (2016), *Nature, 537*.
[18] Ruesch, O. *et al.* (2016), *Nature, 353.*

Acknowledgments: Part of this work is being carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration.

Possible Space Resources and Potential Applications in Future

Yangting LIN

Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China.
LinYT@mail.iggcas.ac.cn

It is no doubt that human being will expand to the Moon, Mars and the whole solar system in future. This progress is being significantly accelerated by the great progresses in science and technology and also by the investment of private companies in space exploration. Proposals of building Moon villages and manned exploring Mars have been discussed in various meetings. In order to sustain human being activities in the whole solar system, there will be large demands for various space resources. On the other hand, there are some highly valued extraterrestrial materials worth transporting back to the Earth.

The potential applications of space resources can be divided into two kinds. A kind of the demands is to obtain specific materials from celestial bodies, which have high values and/ or are very rare in the Earth. A very promising material is ^{3}He, the fuel of future fusion energy. Helium-3 is very rare in the Earth, but highly enriched in the lunar soil via billions years of solar wind implanting. However, news about some asteroids containing several hundred thousand tons of gold (Au) and other precious metals (e.g. platinum, osmium and rhenium), which have a value of trillions US dollars, may not be correct. Asteroids of M-type are metallic Fe-Ni, and some of them can be Au and Pt-group element-enriched, with Au and Pt up to 15g/t and 100g/t, respectively. However, these trace elements are present as solid solution in metallic Fe-Ni. It is definitely uneconomical to extract them via dissolving the metal first in acid solutions.

The other kind of demands is to support human being activities on the Moon and large-scale exploring of the deep space. It is unrealistic and uneconomical to transport all resources and building blocks from the Earth, but to use maximum in situ resources and materials on the Moon and Mars. Because the Moon is bone-dry, water and organic matter are the most valuable resources for the future Moon villages. Besides comets consisting mainly of water ice and organic components, carbonaceous asteroids (C-, D- and P-types) are also rich in water and organics.

Efficient Massively Parallel Prospection for ISRU by Multiple Near-Earth Asteroid Rendezvous using Near-Term Solar Sails and 'Now-Term' Small Spacecraft Solutions

Jan Thimo Grundmann[1], Waldemar Bauer[1], Jens Biele[2], Ralf Boden[3], Matteo Ceriotti[4], Federico Corder[5], Bernd Dachwald[6], Etienne Dumont[1], Christian D. Grimm[1], David Herčík[7], Tra-Mi Ho[1], Rico Jahnke[1], Aaron D. Koch[1], Alexander Koncz[8], Christian Krause[2], Caroline Lange[2], Roy Lichtenheldt[9], Volker Maiwald[1],Tobias Mikschl[10], Eugen Mikulz[1], Sergio Montenegro[1], Ivanka Pelivan[8,15], Alessandro Peloni[4], Dominik Quantius[1], Siebo Reershemius[1], Thomas Renger[1], Johannes Riemann[1], Michael Ruffer[10], Kaname Sasaki[1], Nicole Schmitz[8], Wolfgang Seboldt[11], Patric Seefeldt[1], Peter Spietz[1], Tom Spröwitz[1], Maciej Sznajder[1,12], Simon Tardivel[13], Norbert Tóth[1], Elisabet Wejmo[1], Friederike Wolff[9], Christian Ziach[14]

[1]DLR German Aerospace Center, Institute of Space Systems, Robert-Hooke-Strasse 7, 28359 Bremen, Germany +49-(0)421-24420-1107,
jan.grundmann@dlr.de,
[2]DLR German Aerospace Center, Space Operations and Astronaut Training MUSC, 51147 Köln, Germany
[3]Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), Solar Power Sail ISAS Pre-Project, 3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa, 252-5210, Japan
[4]University of Glasgow, Glasgow, Scotland G12 8QQ, United Kingdom
[5]Telespazio-VEGA, Darmstadt, Germany
[6]Faculty of Aerospace Engineering, FH Aachen University of Applied Sciences, Hohenstaufenallee 6, 52064 Aachen, Germany
[7]Institute for Geophysics and Extraterrestrial Physics, Technical University Braunschweig, Germany
[8]DLR German Aerospace Center, Institute of Planetary Research, Rutherfordstr. 2, 12489 Berlin, Germany
[9]DLR German Aerospace Center, Robotics and Mechatronics Center, 82234 Wessling, Germany
[10]Informatik 8, Universität Würzburg, Am Hubland, 97074 Würzburg, Germany
[11]Consultant to DLR Institute of Space Systems

[12]Institute of Physics, University of Zielona Góra, Szafrana 4a, 65-069 Zielona Góra, Poland
[13]CNES, Future Missions Flight Dynamics, 18 avenue E. Belin, 31401 Toulouse cedex 9, France
[14]High-Tech Gründerfonds Management GmbH, Schlegelstraße 2, 53113 Bonn, Germany
[15]Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

Physical interaction with small solar system bodies (SSSB) is key for in-situ resource utilization (ISRU). The design of mining missions requires good understanding of SSSB properties, including composition, surface and interior structure, and thermal environment. But as the saying goes "If you've seen one asteroid, you've seen one asteroid": Although some patterns may begin to appear, a stable and reliable scheme of SSSB classification still has to be evolved. Identified commonalities would enable generic ISRU technology and spacecraft design approaches with a high degree of re-use. Strategic approaches require much broader in-depth characterization of the SSSB populations of interest to the ISRU community. The DLR-ESTEC GOSSAMER Roadmap Science Working Groups identified target-flexible Multiple Near-Earth asteroid (NEA) Rendezvous (MNR) as one of the missions only feasible with solar sail propulsion, showed the ability to access any inclination and a wide range of heliocentric distances as well as continuous operation close to Earth's orbit where low delta-v objects reside. Also, separated payloads were considered. However, it appears difficult for sailcraft to interact physically with SSSBs. We therefore expand and extend the philosophy of the recently qualified DLR GOSSAMER solar sail deployment technology using multiple sub-spacecraft for deployment. In the same manner, landers are added for one-way investigations or shuttling sample- return. An ideal counterpart for this purpose is the MASCOT nano-lander designed for the JAXA HAYABUSA2 mission to carbonaceous NEA (162173) Ryugu. Shoebox-sized and weighing 11 kg with deployment mechanism, it is compatible with small interplanetary missions designed for piggy-back launch accommodation which enables low-cost massively parallel access to the NEA population. Its unique mobility hopping mechanism was already adapted to the specific needs of long-lived missions with the MASCOT2 design for ESA's AIM spacecraft in the NASA-ESA mission AIDA to binary NEA (65803) Didymos. A shuttling sample-return lander similar in size to PHILAE is being studied for the JAXA Solar Power Sail mission, OKEANOS. The methods enabing the realization of MASCOT such as Concurrent Engineering, Constraints-Driven Engineering and Concurrent Assembly Integration and Verification enable responsive missions based on re-used, re-purposed or now available as well as near-term technologies. Integrating these by Model-Based System Engineering (MBSE) will lead to further streamling of hardware and mission implementation. With the thus raised efficiency of mission implementation and a piggy-back launched small spacecraft approach, institutional as well as commercial asteroid users are enabled to move on from single-trail traverses to broad area surveys of the asteroid population. The ability to visit multiple targets per spacecraft and to change, even select targets only after launch also decouples the mission from the pre-launch state of ground-based target observations. The mission can grow in flight with the growth of knowledge on asteroids on the ground. While actual mining and even preparatory missions will require larger payloads, the performance of present sail technology is sufficient to undertake initial surveys, on the basis of well-established and trusted transparently peer-reviewed planetary science methods, to open up this new frontier to new enterprises.

Extensive Exploration of Small bodies with Autonomous Navigation

Marco Agnan[1], Daniel Hestroffer[3, 4], Boris Segret[2], Jordan Vannitsen[1, 5], Gary Quinsac[4, 2]

[1]ODESSYUS Space Inc, Tainan, Taiwan
[2]Observatory of Paris, E.S.E.P, Meudon, France
[3] IMCCE, Observatory of Paris, CNRS, UPMC, Univ. Lille, Paris, France
[4] Paris Science Lettre Research University, France
[5] National Cheng Kung University, Tainan, Taiwan

Due to remote distances and low gravity, exploring small bodies of the Solar system (such as asteroids or comets) remain a very complex task. For Rosetta, the exploration strategy involved a heavy data exchange (including raw images of the NAVCAM) between the space segment and the ground segment, supported by an important operational team.

In the context of NewSpace, developing autonomous ways to operate remote and/or numerous space systems will be critical. Because of more and more small satellites are being launched in solo or network/swarms missions, the operational cost of such projects is booming, especially because of the required ground segment. This kind of technology could greatly increase the feasibility of such projects (by moving the decision making to the satellite), and reduce the operational cost, for numerous applications, such as high frequency imaging of the Earth, Radio Interferometry from space, simultaneous multi---point in situ study of the Solar Wind, or for the exploration of small bodies both for science and prospection for space mining… A performant autonomous navigation function for small satellites could unlock new scientific missions and commercial applications.

For example, for Small bodies exploration, bringing a CubeSat that could autonomously navigate in the vicinity of small bodies would be an ideal platform to perform science from multiple locations that are be too risky for a big mothercraft controlled from Earth.

This presentation will introduce the BIRDY autonomous navigation technology and the new opportunities that would be unlocked, both for science and business.
This Autonomous Guidance, Navigation and Control for small satellite, named BIRDY, and is currently being developed by a Consortium made of laboratories LESIA and IMCCE from Observatory of Paris in France, and the National Cheng Kung University and ODESSYUS Space in Taiwan.

This work has been supported by Labex ESEP (ANR N° 2011---LABX---030

Wrap Up: How to Improve our Knowledge

Simon F. Green

The Open University, Milton Keynes

While dynamical accessibility remains a key factor in the determination of which NEAs are suitable for the first attempts at ISRU, the expected composition of a chosen target is of fundamental importance. Evidence from the meteoritical record indicates a diversity of composition and degree of past thermal and aqueous processing of asteroidal material. Asteroid taxonomy from photometric and spectroscopic remote sensing re;lects this diversity, although the limitations of such observational evidence preclude direct correlations between many of the meteorite and asteroid classes. ASIME 2018 focuses on the 'asteroid composition' theme of the science knowledge gaps that emerged from the 2016 ASIME, summarised in the resulting white paper (https:// arxiv.org/abs/1612.00709). I will review the questions on asteroid composition relevant for asteroid mining and guide the discussion of what we (think we) know, and how we can improve our knowledge through upcoming missions, surveys and targeted observations and potential future exploratory or reconnaissance missions.

Abstracts Without a Corresponding Presentation

Probing Asteroid Surface Layers

Line Drube and Alan Harris

German Aerospace Center, Rutherfordstr. 2, 12489 Berlin,
+49 (0) 3067055-0, alan.harris@dlr.de; line.drube@dlr.de

Some prior knowledge of the surface properties of the target is important for the success of all types of lander missions to asteroids.

Astronomical observations in the visible region provide some information on surface properties but other techniques are required for more detailed insight. For example, the asteroids Eros and Itokawa have similar albedos and spectral types, however the NEAR Shoemaker and Hayabusa missions saw very different surfaces when they arrived: Eros is covered by fine regolith in contrast to Itokawa's coarser, rubble-like regolith. Thermal infrared telescopic data had enabled this to be predicted, as the surface thermal inertia (Γ=($\kappa\rho$ C)0.5) values of the two asteroids are very different. However, the calculation of thermal inertia using thermophysical models requires high quality thermal-infrared observations taken at different times, a shape model and spin state information. These demanding requirements have limited the number of asteroids with measured thermal inertia to ~60 so far (Delbo et al. 2015, Asteroids IV, p.107-128, and references therein).

Here we discuss a novel means to easily estimate the thermal inertia of any asteroid based on knowledge of its astrometric geometry, spin axis and thermal-infrared emission. We refer to it as the NEATM Thermal Inertia Estimator (Harris & Drube 2016, Astrophysical J., 832:127). The rms fractional difference between the estimator's thermal-inertia values and those calculated by detailed thermophysical modeling is only 40%, which is encouraging given that thermal inertia values of small solar-system bodies cover over 4 orders of magnitude and the thermophysically- modeled thermal inertia themselves are affected by relative uncertainties of the order of 50-100% (Delbo et al. 2015, Asteroids IV, p.107-128).

Using our technique we have estimated thermal-inertia values of over 700 asteroids and have noted some interesting trends in the data, e.g. results appear to imply that the thermal inertia of near-Earth objects, and therefore the density and thermal conductivity of near-surface material, increases rapidly with depth within the topmost 1m.

We briefly describe the relevant observational results and analysis, and discuss the implications for asteroid lander missions.

Direct Observations of Asteroid Interior for Exploration and Mining

A.Herique1, W. Kofmann[2], D. Plecemeier [3]
[1]Univ. Grenoble Alpes, IPAG, Grenoble, France, alain.herique@univ-grenoble-alpes.fr
[2]Space Research Centre, PAS, 00-001 Warsaw, Poland
[3]Dresden University of Technology, Chair for RF Engineering, Dresden, Germany

Our knowledge of the internal structure of asteroids entirely relies on inferences from remote sensing observations of the surface and theoretical modeling [1]. Is the body a monolithic piece of rock or a rubble-pile, how high is the porosity? What is the typical size of the constituent blocs? Are these blocs homogeneous or heterogeneous? The body is covered by a regolith whose properties remain largely unknown in term of depth, size distribution and spatial variability. Is it resulting from fine particles re-accretion or from thermal fracturing?

After several asteroid orbiting missions, theses crucial and yet basic questions remain open. Direct measurements of asteroid deep interior and regolith structure are needed to better understand the asteroid accretion and dynamical evolution and to provide answers that will directly improve our ability to understand structures and dynamical processes. Probing of the interior is also crucial for determining material composition and mineralogy. Space weathering alters the uppermost few microns of asteroid surface materials while thermal cycling affects greater depths. Therefore, surface properties as observed by optical remote sensing may not be representative of the interior mineralogy and chemical composition.

Direct observation of asteroid subsurface are also required to better model mechanics of such kind of granular materials in low gravity. This is crucial to plan any interaction of a spacecraft with an asteroid for exploration or sample return purposes, and for any mining activity in the future.

Radars operating at a distance from a spacecraft are the only instruments capable of achieving this objective of characterizing the internal structure and heterogeneity from submetric to global scale, for the benefit of science as well as for planetary defense or exploration. Two complementary radars, opera3ng at different frequencies, are needed to meet the objectives requirements [1]. The deep interior structure tomography requires a low-frequency radar (LFR - inheriting form Consert/Rosetta), in order to propagate throughout the complete body and characterize the deep interior. The characterization of the first ten meters of the subsurface with a metric resolution, to identify layering and to reconnect surface measurements to internal structure, will be achieved with a higher frequency radar (HFR --- inheriting from WISDOM/ExoMars). The low and high frequencies radars have been redesigned in the frame of the AIDA/AIM phase AB [2,3] and for HERA/ESA mission. These instruments have been proposed for the next M4 and M5 classes European missions. They are under discussion for future missions like SPS/Jaxa to Jupiter Trojans or Discovery missions.

We will present the rationale of asteroid interior investigation, proposed instruments suite and science return.

[1] Herique, A., et al., 2017. Direct Observations of Asteroid Interior and Regolith Structure: Science Measurement Requirements, ASR, doi:10.1016/j.asr.2017.10.020.
[2] Michel, P. et al., 2016. "Science case for the Asteroid Impact Mission (AIM): A component of the Asteroid Impact & Deflection Assessment (AIDA) mission." ASR (57): 2529–2547.
[3] Herique, A., et al., 2018. A radar package for asteroid subsurface investiga3ons: implica3ons of implemen3ng and integration into the mascot nanoscale landing platform from science requirements to baseline design, Acta Astronomica, under review

Realistic Simulation Results for CubeSat-based Asteroid Tomography

Mika Takala

Tampere University of Technology, PO Box 527, FI-33101 Tampere, Finland, mika.takala@tut.fi,

In recent years, interest towards using CubeSats to accompany planetary missions has increased. This presentation concentrates on the possibility to perform CubeSat-based tomographic radio frequency measurements with a near-Earth asteroid (NEA) as a target, as NEAs present a challenging, but achievable target for an independent CubeSat mission.

The inversion results obtained with numerically simulated radar measurements will be presented. These simulations were performed to validate the radar modeling approach of the DISCUS (Deep Interior Scanning CubeSat) mission concept in which two identical CubeSats carry a bistatic stepped-frequency 20 MHz center frequency radar. The target of the DISCUS is a rubble pile NEA. The simulations examined a synthetic NEA model based on the shape model of the asteroid 1998 KY26 scaled to 550 m diameter. The interior structure comprised a surface layer and macroporosity structures (cavities). The simulated distance was 5 km, which is deemed to be achievable with CubeSat technology.

The results suggest, that a volumetric reconstruction of the asteroid interior is achievable if the total noise, i.e., the net effect of the cosmic background radiation and modeling errors, is sufficiently low. The main factors limiting the quality of the inverse estimates are the power available for the radar transmission (10 W transmitted), the total noise in the measurements, the accuracy of the position measurement, and also that of the asteroid shape model.

Birdy Interplanetary CubeSat for Planetary Geodesy

Daniel Hestroffer[1], M. Agnan[2,3], B. Segret4, H. Chen[1], J. Vannitsen[2,3], G. Quinsac[4], P. Rosenblac[5], S. Bertone[6]

[1]IMCCE, Paris observatory, Université PSL, CNRS,
Paris, France
[2]ODYSSEUS Space Inc., Tainan, Taiwan
[2]National Cheng Kung University, Tainan, Taiwan
[3]LESIA, Paris observatory, Université PSL, CNRS, Paris, France
[4]ACRI---ST, Toulouse, France
[5]Astronomical Institute, University of Bern, Bern Switzerland

We are developing the Birdy concept of a scientific interplanetary Cubesat, for cruise, or proximity operations around a Small body of the Solar System (asteroid, comet, irregular satellite). The scientific aim is to characterise the body's shape, gravity field, and internal structure through imaging and radio--science techniques. Indeed, knowledge of the actual mass and bulk--porosity is important for most operations, and asteroid exploita3on; these fundamental parameters can be obtained thanks to radio--science and dedicated instruments. Radio--science is now of common use in planetary science (flybys or orbiters) to derive the mass of the scien3fic target and possibly higher order terms of its gravity field. Its application to a nano--satellite brings the advantage of enabling low orbits that can get closer to the body's surface, hence increasing the SNR for precise orbit determination (POD), with a fully dedicated instrument. This is of particular interest for low--gravity, low--mass asteroids. Additionally, it can be applied to two or more satellites, on a leading--trailing trajectory, to improve the gravity field determination. We will present the general scheme of BIRDY - to be associated to a future mission to a small body -current status and development plan.