WRAP UP:
HOW TO IMPROVE OUR KNOWLEDGE

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Objective

Mining objectives focused on water

- I will not:
  - review the meeting's presentations
  - give a balanced view (my ignorance is wide-ranging)
- I will try to:
  - Concentrate on NEA composition
  - Summarise: what (I think) we know
    - what (I think) we need to know
    - what (I think) are important issues
  - Link discussion to answers to list of questions
- Much of what I say may not be correct
  - Please tell me why as we go along …

Potential targets

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What we know

- Dedicated surveys
  - >18 000 NEAS discovered; >1000 pa
  - >50% smaller than 140 m; sizes down to a few metres
  - can identify accessible targets: low Δ-V (low *e*, *i*; *a* ~1 AU)
- New surveys (Gaia, LSST) will increase discoveries
  - May be serendipitous data in other surveys

Q10. [revisit] Is there any evidence that the orbit of an asteroid provides information on its composition?

- Yes, but orbits only give statistical inference on spectral type so cannot alone be relied upon to identify targets

Potential targets

What we need

- Follow-up and characterisation of targets
  - large enough for follow-up spectroscopic observations
  - require physical characterisation – e.g. exclude fast rotators

Follow-up at discovery apparition if possible
  - Likely brightest at discovery
  - potential long delay until next good apparition

- Size range 30 – 100 m
  - Too few at larger sizes

Q9. [revisit] Is there any evidence that the shape of an asteroid provides information on its composition?

- No ???

Q2. [revisit] How can the rate of spectral characterisation of NEOs be increased? It lags far behind discovery rate, especially at smaller sizes (D < 300m).

- Requires dedicated follow-up programmes at discovery

Potential targets

Issues

- Small number of targets?
  - especially if 0.7 μm feature is discriminant
  - further reduced by spin period constraint
- Large telescope access?
  - Continuous access required for discovery apparition follow-up
  - New facilities too expensive
  - Buy time on public facilities?
    - Data will be open.
    - Probably not enough time available
  - ”take over’ redundant 4 to 8-m class telescope(s)
    - 8 m unlikely for at least a decade
    - Running costs still high – who pays?
  - Follow-up for small targets requires facilities as large as discovery

Remote spectroscopy

What we know

- Spectroscopy: ~2500 asteroids in visible, many fewer in IR
- Spectrophotometry: ~60 000 in 3-8 wavebands
- Wide diversity of spectral types in NEO population
- Primitive objects have relatively featureless spectra
- Presence of hydrated minerals can be identified
    - Through 3 μm feature
    - In thermal IR
    - By 0.7 μm feature (not exclusive)
- Growing understanding of affects of space weathering on low albedo asteroid spectra
- **Q6.** [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?
    - None! (low-q periods, obliquity changes).
    - If present not detectable from remote sensing

Remote spectroscopy

What we need

- Visible/IR spectroscopy/spectrophotometry
  - Small fraction of small low Δ–V objects have spectra
  - Requires large telescopes and/or immediate follow-up
- Identification of hydrated minerals

Q3. 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?

- Useful for initial identification of primitive types
- Careful choice of filters can indicate presence of some features
- Benefits of easy observation (and large surveys?)

Q5. [revisit] How can the water absorption feature at 3.1 μm 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?

- 3.1 μm feature most diagnostic, but not possible for most targets?
- In-situ data (see later)

Remote spectroscopy

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Issues

- Data mostly for MBAs and larger objects: Very few small NEAs
- Small numbers of primitive asteroids with hydrated minerals?
- 3.1 μm feature best proxy for water content
  but not accessible for most potential targets?
  - Smaller targets have S/N too low?
  - Near 1 AU (where best low Δ–V targets reside)
    region is dominated by thermal emission
  - Space-based system doesn't help
- 0.7 μm feature easiest to detect
  - Fe_2^+ Fe_3^+ feature – always associated with 3.1 μm OH
  - Only seen in fraction of cases where 3.1 μm feature is seen

Remote spectroscopy

Issues

- Other diagnostics:
  - 0.9 μm – no benefit over 07 μm
  - 2.4 μm X-OH – very weak
  - ~6.5 μm mineral bound H_2O emissions – requires spacecraft
  - 8-12 μm silicate/phyllosilicate CF – requires large telescope with thermal IR spectrometer or spacecraft and large/close targets
- Spatial variations in spectra of small NEAs
  - In-situ measurements don't not show (significant) heterogeneity but small asteroids (Eros, Itokawa, Gaspra) not primitive
  - Variation may be linked to YORPoid surface mobility? Ryugu/Bennu test?

Q11. [revisit] What highest value telescopic composition/characterisation studies are not being pursued for lack of funding or perceived low priority from space agencies?

- All of them!

Asteroid – meteorite links

What we know

- Detailed knowledge of meteorite composition
  - Highly heterogeneous at microscopic scales

Q22. What is the state of the art regarding matching meteorite spectra to asteroid spectra, and matching artificially weathered meteorite spectra to asteroid spectra?

Q15. [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?

Q21. [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?

- Broad understanding of many (but not all) links
- Hayabusa samples match predictions from Itokawa spectra
- Weathering understood and verified for S-types
- Growing understanding of dark asteroid weathering effects from lab analogues

Asteroid – meteorite links

What we need

- Samples from primitive asteroids
  - Hayabusa 2 and OSIRIS-Rex will return samples soon

Issues

- Heterogeneity of meteorites?
  - Almahatta-Sitta has mixture of evolved and primitive material
  - This is at microscopic scales: macroscopic regolith mix uniform?
  - But, it complicates linking composition and spectra

Q14. [revisit] We could develop asteroid material simulants based on meteorites; how well do meteorites represent the NEO population, especially at larger (D > 10m) sizes?

- Meteorite selection effects: atmospheric entry mitigates against low strength, primitive objects
- most common primitive types not sampled?

In-situ measurements

What we know

- Morphology studied for a few asteroids
  - surface mobility identified: seismic shaking, landslips, ponding…
- Physical properties:
  - No lander measurements (sample returns are touch & go)
  - Limited regolith properties (grain size, cohesion) inferred from mid-IR observations/thermal models
  - potential indirect data from DART/Hera?

What we need

- Physical measurements
  - Surface measurements from reconnaissance missions? constrain physical analogues?

In-situ measurements

Issues

- Timescales for science exploration missions

  - missions with small landers proposed but not so far selected

Q4. Technically, and scientifically, how does spectroscopy of an asteroid at short (km range) distances differ from spectroscopy with ground--based telescopes?

- Same limitations of top few microns
- Spatial resolution will allow study of spectral diversity (if present)
- 3 μm feature possible (for low temperature latitudes)

Q1. [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?

- Can't get 100% confidence without landing?

Remote sensing: Near IR 3um and mid-IR spectrometers

X-ray spectrometry gives elemental abundances (O but not H)

Neutron spectrometry for H (water inferred)

Surface instruments: mass spectrometers, GC-MS, LA-MS etc.

In-situ measurements

Issues

Q7. [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?

- Neutron spectrometry for H (water inferred)
- Penetrates <~ 1 m?
- Less than orbital thermal processing/gardening skin depth
- Low signal so spatial resolution will be a problem

Q18. [revisit] What proximity observations and measurements would better link remote observations to meteorite studies?

- resolved spectroscopy to identify heterogeneity
- lander analysis (composition and physical properties)
- returned samples MUCH more valuable

Laboratory measurements

What we know

- Vast knowledge of meteorite composition
    - at scales down to nm
- Simulants

Q13. [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?

- chemical simulants of use for in-situ instrument testing only?
- physical simulants important for: mining processes
  stability of landers/facilities on surface

What we need

- Samples from confirmed primitive asteroids
    - Will get from Hayabusa2 and OSIRIS Rex

Laboratory measurements

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Issues

- Laboratory spectroscopy not direct analogue of remote sensing?
  - reflectance dependent on scattering angle (observation geometry)
  - but still very valuable….
  - thermal spectra require same environment (thermal gradient critically affects spectrum)
  - grain-size dependent results
- Some CM chondrites are thermally altered, dehydrated
  - Tagish lake regarded as primitive D-type analogue but appears to be thermally dehydrated??
  - Not a problem for mining: spectral signature required for target

Reconnaissance missions?

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Discovery
Surveys → low Δ–v objects
H indicates size

D ~ 30 – 100 m

Follow-up observations:
(4 colour spectrophotometry, 0.7 μm feature from spectra)
(light curves)

Primitive spectral type,
Hydrated mineral signature
$P > P_{crit}$

Reconnaissance orbiter mission
(resolved visNIR and thermal spectroscopy, tomography?
Neutron detector?

Landing or surface probe
Physical measurements
Direct chemical/elemental measurements

Mining process
Test mission

Questions not addressed

Q12. [revisit] What observable phenomenon can help constrain the potential presence of resources from ballistic experiments such as Hayabusa-II's SCI (Small Carry-on Impactor) experiment?

Q16. [revisit] What signatures of past water of hydrated minerals could be observed on an asteroid surface that might indicate subsurface water or hydrated minerals?

Q17. [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?

Q19. 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?

Q20. [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?

Q23. 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?

Q24. [revisit] Processing of mined materials will depend on composition and structure of the asteroid, and is a matter of engineering; is it necessary to develop these methods in the near future or can it be postponed until the asteroid mining industry is more mature?

Questions for review

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Asteroid surveys

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