Ref. Ares(2016)616390 - 04/02/2016

Mission Overview and Timeline Document

Introduction

This document outlines both the known and *assumed* mission architectures of robotic exploration missions to return samples from different Solar System target bodies – Mars (and its moons), the Moon and asteroids. It also provides a broad introduction to the geological properties of the surfaces of these bodies which will indicate the types of material that is expected to be returned from anticipated sample return missions.

Currently (2015) there are only two Solar System sample return (SR) missions that are in operation or being assembled – the Japanese Space Agency (JAXA) Haybusa 2 mission and the NASA OSIRIS-Rex mission, both these missions are visiting carbonaceous asteroids.

Recent proposals for asteroid SR missions have been made to ESA (MarcoPolo, MarcoPolo-R and MarcoPolo-R and MarcoPolo-2D), however these have been ultimately unsuccessful and these missions have not been selected for detailed study.

There are currently no formalised Mars SR missions from any space agency although it is a stated ambition by a number of agencies and space faring countries to obtain samples from Mars through SR missions. NASA is currently preparing its next Mars lander mission (Mars2020), which is designed to collect samples and 'cache' them for potential future return by follow-up missions.

ESA and Russian Space Agency have also carried out a number of studies into SR missions to the moons of Mars (Phobos and Deimos). Finally, there are also early stage plans in place for SR mission(s) to the South Pole region of the Moon.

Mars Sample Return Missions

Mars SR has been long seen as the next major step in the exploration of Mars and a critical strategic goal with the ultimate aim of putting humans on Mars. As is the case for the SR missions described above there are several engineering and technical challenges for Mars SR, however the most significant complicating factor is that Mars samples have stringent Planetary Protection requirements governing their collection and subsequent return to Earth. These requirements add complexity to mission architecture where both mission and hardware design are used to 'break the chain' of contact between Mars and Earth. A large number of reports describe possible mission architectures for Mars SR missions.

NASA Mars2020

The NASA Mars 2020 rover is not generally regarded as a Mars SR mission, however a major element of its mission to Mars will be to collect samples of interest and then cache them for *potential* collection at some later date. If these samples are indeed collected by a TBD later mission then the Mars2020 mission would be considered as a the first part of a Mars SR.

The Mars2020 rover builds on heritage from the current NASA Mars Science Laboratory *Curiosity*, however has a suite of new scientific payload instruments as well as the added capability to collect and cache samples. The instruments selected for the Mars2020 rover were chosen specifically to allow the selection of the most promising samples for acquisition and subsequent caching.

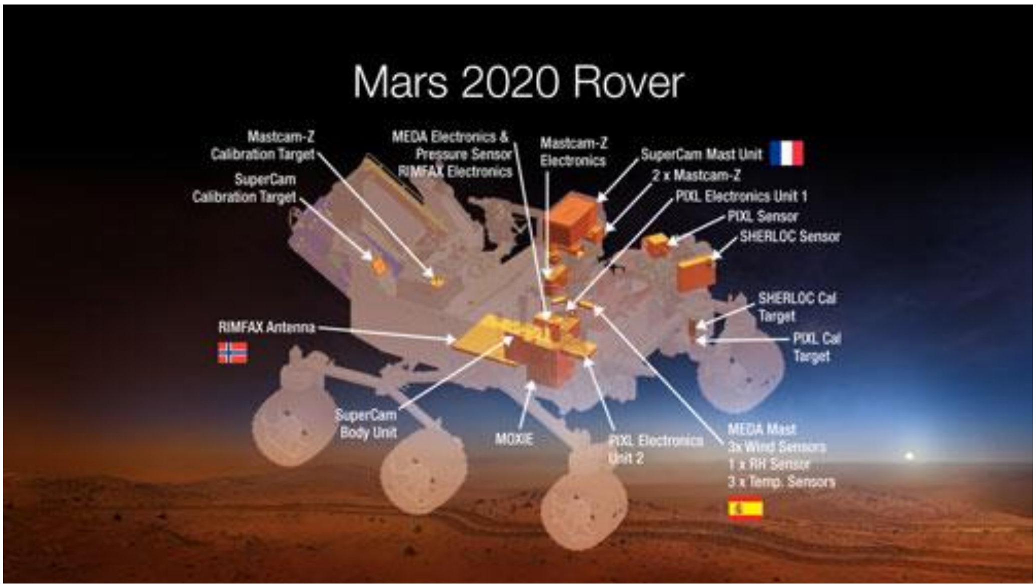

Fig. 1. Schematic of the proposed NASA Mars2020 mission. Note that three of the instruments are provided by European countries. Image from http://mars.nasa.gov/mars2020/mission/overview/.

The mission timeline indicates launch of the spacecraft in summer 2020 with arrival at Mars in early 2021. Once the rover lands on Mars, its primary mission is scheduled for one martian year (669 days).

Samples collected by the rover will be in the form of small cores of geological material 5 cm long and approximately pencil width in size, weighing ~15 g each, from ~ 30 different samples/locations. These cores would then be placed into a clean sample tube and hermetically sealed. Initial plans were to place a TBD number of these tubes into a single cache which could then be recovered at a later date. More recent studies by engineers and scientists at the Jet Propulsion Laboratory have suggested an alternative scenario known as 'adaptive caching', whereby the individual sample tubes are cached either individually or in small groups on the surface of Mars, rather than being cached in a single container (Farley and Williford, 2015).

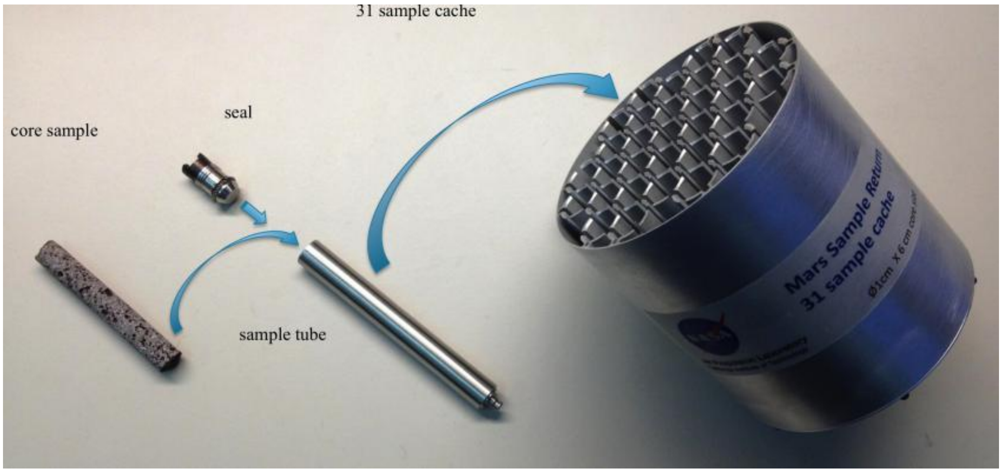

Fig. 2 Image showing a sample showing the sample tube and single cahche container as has been proposed for the NASA Mars 2020 mission. Each core of sample weighs ~15 g and is about 5 cm in length and is pencil width. From http://photojournal.jpl.nasa.gov/catalog/PIA17277

Fig 3. Timeline for the Mars2020 mission with an anticipated summer 2020 launch. http://mars.nasa.gov/mars2020/images/08_mission_timeline-full.jpg

International Mars Sample Return

The iMARS report (2008) provides an assessment of a proposed mission architecture including both mission and science architecture for a future international Mars SR campaign. This report provides a detailed timeline with a number of different scenarios including, for example, telecommunications support from a mission that is already in operation around Mars. Key findings from the iMARS report are:

- To be able to answer the key science questions and to be acceptable to the international scientific community, the mission would need to return carefully selected samples and geologically diverse samples. These samples would need to be carefully controlled at all stages of the end-to-end mission, including both the flight and ground segments (i.e. in the Sample Receiving Facility(ies) and Curation Facility(ies)).
- Different elements of the mission were identified that could be led or supported by different international participants.
- Five mission design options were identified using launch opportunities from 2018-2022. All these options would include two launches and at least one Sample Receiving Facility certified prior to the return of any samples.
- New technology developments for the flight elements and the Sample Receiving Facility(ies) will require a long lead time. In both cases "substantive effort must begin at least 10 years before launch of the flight segment".
- Public outreach and communication is very important and needs to be addressed in an "open and well-managed way from the very beginning".

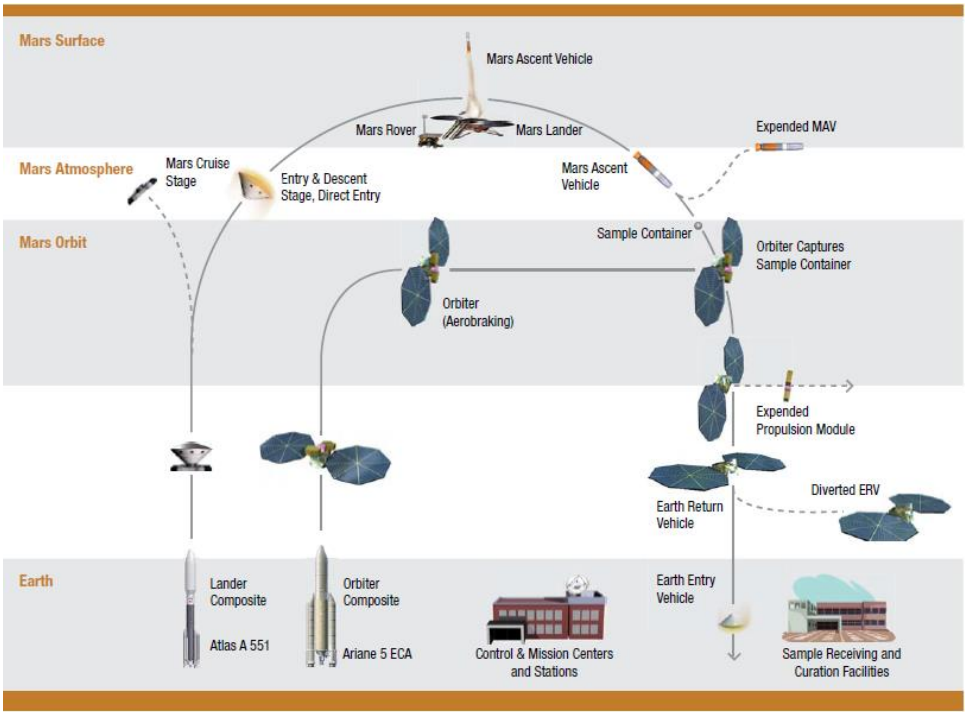

Fig. 4. Reference architecture as used in iMARS (2008). Two launches of spacecraft are required in addition to ground based elements such as mission control centres and Sample Receiving and Curation facilities.

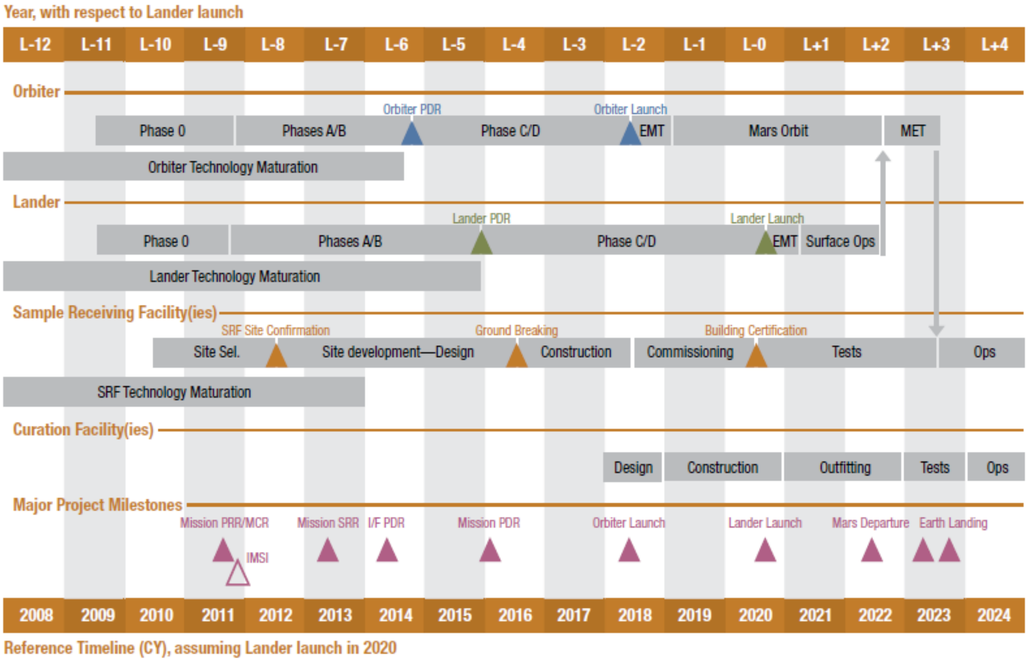

Fig. 5. A proposed timeline from the iMARS report (2008) showing the timescales and development milestones for a Mars SR mission. Note that the Sample Receiving Facility(ies) begin construction prior to the launch of any spacecraft and ~8 years prior to samples returning to Earth.

Mars Geology Overview

The exploration of the planet Mars is considered a high-priority by both ESA and NASA owing to the fact that many lines of evidence point to the fact that in its past, it had an environment that was perhaps suitable for life. This evidence has been gathered over the last ~40 years by robotic exploration missions e.g. NASA's Viking, Mars Exploration Rover and Mars Science Laboratory missions; Mars orbiter missions such as ESA's Mars Express mission and also through the detailed study of Martian meteorites using laboratories on Earth. Future missions to Mars will be met with interesting challenges due to the unique environment that exists at the Martian surface and within the shallow subsurface (uppermost ~1m). As has been demonstrated through previous exploration, both through global scale orbital remote sensing and local scale (100s of metres to kilometres) in-situ analyses by rovers, the surface environment is composed of an oxidized and likely chemical reactive mixture of very fine grained dust with silt, sand, cobbles and boulders. Exposures of bedrock exist, though most of the surface is generally composed of impact-fragmented regolith. While the surface of Mars is diverse and geologically dynamic, it is in fact much more homogenous than the surface Earth's surface (Christensen et al., 2001) As such, it is useful to describe the surface in general terms, as vast portions of Mars are relatively homogenous.

Early telescopic observations of the Mars showed that the surface is a two-component system of dark and light materials. The modern view is basically unchanged: Mars contains vast areas of light-toned terrain that is composed of dust and large portions of dark regions, which are generally volcanic (Bell et al., 1997).

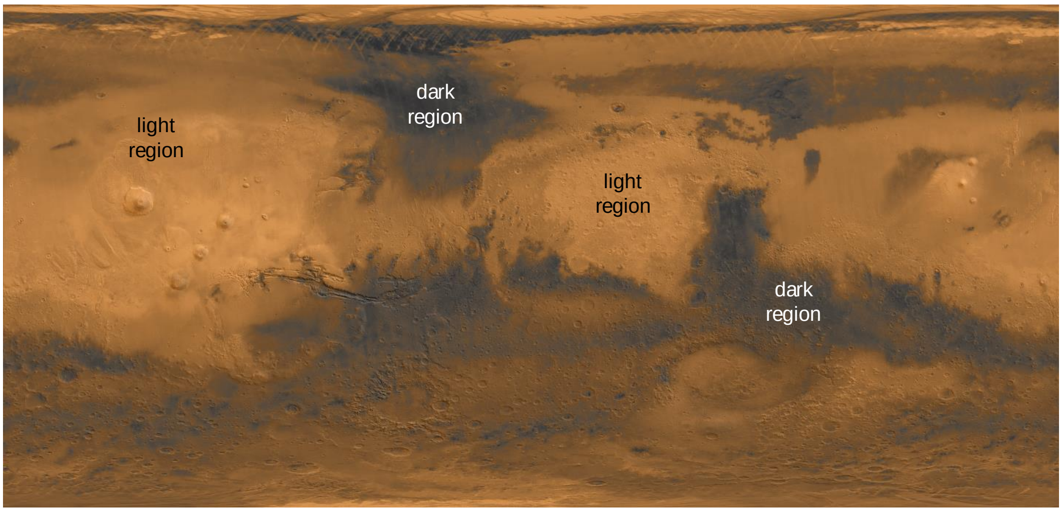

Fig. 6. Global view of Mars. TES albedo data show that the surface contains vast areas of bright, dusty deposits and dark, relatively low dust surface areas.

Early results hinted at a mafic volcanic (basaltic) composition of the dark material based on the observation of an electronic absorption indicative of Fe-bearing pyroxenes. Decades later, global reconnaissance of the surface with orbital infrared spectrometers has supported that interpretation and demonstrated conclusively that the surface is dominated by materials of basaltic composition. Note the orbital imaging cameras, thermal and infrared remote sensing instruments observe only the uppermost 10s to 100s µm of the surface and so our little knowledge of the localised surface at even very shallow depths is dependent on the information gathered by rovers where abrasion tools (e.g. on the Mars Exploration Rovers or coring tools (Mars Science Laboratory)) have been used to expose up to 5 cm into rock outcrops or the rover locomotion system has been used to create 'trenches' in the regolith to observe and make measurements at a few centimetres depth.

The most basic view of Mars' surface composition comes from the global view of the planet returned from the Gamma Ray Spectrometer (GRS) aboard NASA's Mars Odyssey mission. The GRS was sensitive to the elemental composition of the uppermost ~1 meter of the Martian surface (though the detection depth or "z" is different for each element). The results generally indicate that, in light or dark regions, the surface has an elemental composition of Fe-rich basalt (McSween et al., 2009; McSween et al, 2010). From the mid-infrared (wavelengths of ~5-40 microns) point of view (results from the Thermal Emission Spectrometer), the surface is dominated by pyroxene, plagioclase, olivine and dust. The igneous minerals – olivine, plagioclase and pyroxene – are similar to those observed within known Martian meteorites (Christensen et al., 2000; Hamilton et al., 2001). However, most of the Martian meteorites are composed nearly exclusively of pyroxene and olivine, with only minor abundances of plagioclase. In contrast, the Martian surface seems to contain up to 40-50% plagioclase. This is thought to be potentially explainable through weathering processes: perhaps Martian meteorites provide a more representative view of the bulk crust, but more plagioclase is observed in the surface environment than in the bulk rock because plagioclase is relatively more resistant to weathering than olivine and pyroxene. This issue is open to debate. For missions that propose 'deep' sampling of the Martian crust it is a pragmatic to consider the composition of Martian meteorites, which are predominantly basaltic in composition.

More recent views of the surface from the near infrared (wavelengths of ~0.5-4 microns) have revealed improved global maps and more detail at the local scale i.e. a few hundreds of metres or few kilometres. Data from the *Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité* (OMEGA) and the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) have revealed new insights into the distribution, geologic context and crystal chemistry of Martian surface materials (Bibring et al., 2006; Murchie et al., 2009). These results demonstrate conclusively that Mars is dominated by pyroxene and olivine of various compositions, though the near infrared data are not sensitive to plagioclase unless the plagioclase contains significant amounts of Fe.

The near infrared results also produced another interesting result relevant to surface properties. Mafic glass is a material that is expected to occur on Mars because it is produced in explosive mafic volcanoes, which Mars has, and because it is formed in meteor impacts into mafic terrains, which are extremely common. Basaltic glass is of interest because it would likely be highly reactive with the surface environment and would be an interesting target for future missions. While the mid-infrared techniques were not well suited to detect basaltic glass, the near infrared techniques have shown significant amounts.

In summary, the dark regions of Mars are largely composed of igneous minerals. Any mission to a Martian dark region will likely encounter regolith dominated by pyroxene, olivine, plagioclase, and basaltic glass.

Light toned regions of Mars are much more homogeneous than the dark regions. This is because the light regions are composed of fine-grained dust, which is thought to be either somewhat or potentially thoroughly homogenized. The geologic nature of the dust is not well understood; though it is presumably composed of volcanic ash, impact generated fines, and the products of physical degradation of the surface by wind.
The dust has been measured spectroscopically using mid-infrared and near-infrared techniques. Near infrared results have long been recognized as evidence for Fe-oxides, specifically nanophase (poorly crystalline) Fe-oxides (Morris et al., 2001). Near IR spectra of the dust bear a strong similarity to oxidized, hydrated volcanic glass sampled from arid regions of Hawaii. This Hawaii glass is generally referred to a "palagonite", which is a multi-phase mixture of hydrated glass, nanophase clays (smectites) and Fe-oxides, with minor occurrences of zeolites, opal, carbonate, sulphate, and phosphates (Morris et al., 2001). Mid IR results are consistent with the near IR; TES results show that the dust is composed largely of hydrated silicate material with minor abundances of oxides (Ruff and Christensen, 2002).

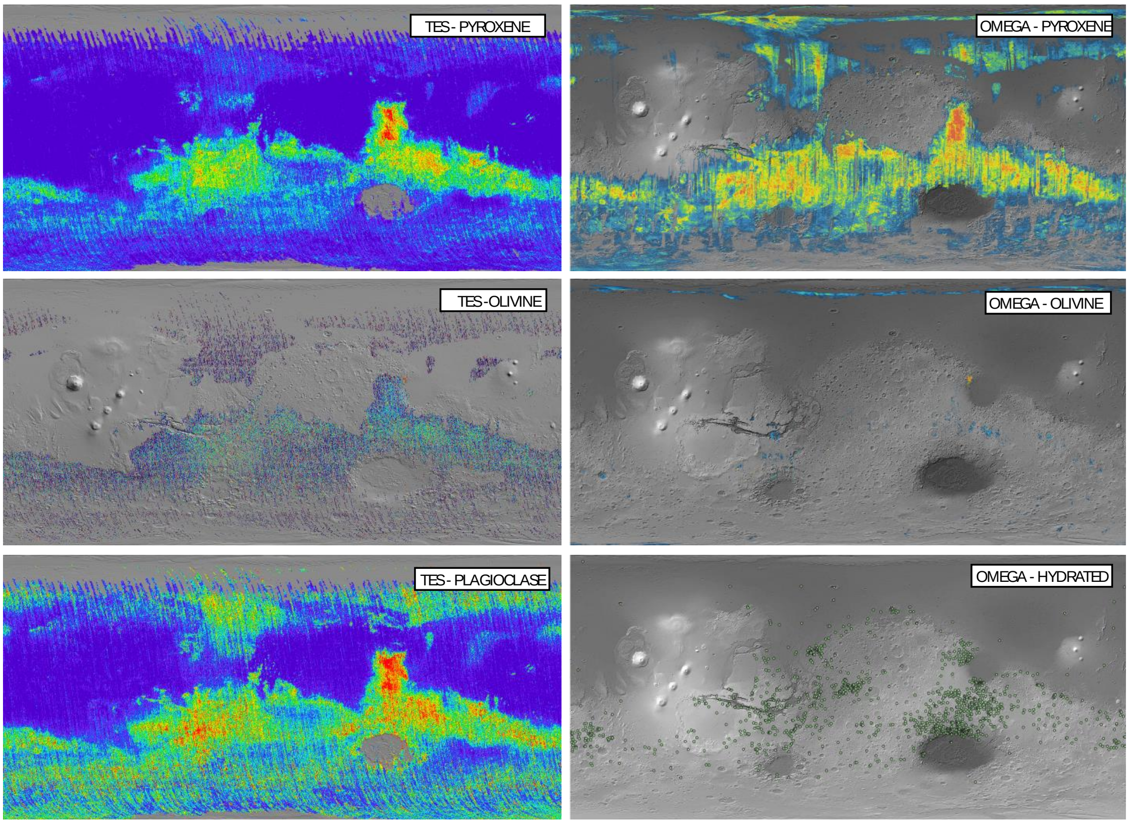

Fig. 7. Global mineralogical data from thermal infrared (TES) and near infrared (OMEGA) reveal the surface composition of Mars. TES maps include pyroxene, olivine and plagioclase. OMEGA maps include pyroxene, olivine and "hydrated minerals."

The primary mechanism by which we can evaluate the physical properties of surface material on Mars remotely is through the measurement of thermo-physical and spectroscopic properties of the surface. In the case of certain, large hazards, such as boulders and rough bedrock, the surfaces can be imaged directly. But, many other properties are more difficult to directly measure. In particular, grain size, slope, and small-scale roughness need to be estimated through indirect means.

The primary datasets used for characterizing physical surface properties of Mars are thermal infrared data from TES and the Thermal Infrared Imaging System for Mars (THEMIS) (Christensen et al., 2000). TES measured surface albedo and temperature at spatial scales of 10s of km of the entire surface. THEMIS has now completed the same measurements at 100-metre-scales for the entire surface. By measuring temperature in the daytime and night-time, it is possible to calculate how solar energy is stored and released in the uppermost decimetres of the surface (thermal inertia). The measured thermal inertia of a surface can then be used to constrain the grain size of the material. Very low values (30-60) correspond to pure dust. Very high values (>1000) correspond to bedrock. Values in between correspond to surfaces with various combinations of sand, silt, cobbles and bedrock

The Martian regolith has been much studied by the various lander missions that have visited Mars and observations from orbiters that can provide information as to the physical properties of the surface based on images, albedo, topography and thermal inertia measurements. The surface regolith, or soil, is made up of small fragments of pebbles, granules, sand and finer material and is unconsolidated or poorly consolidated. The regolith is produced through a combination of Martian geological/weathering processes such as the physical reworking of the surface through meteorite impact (impact gardening), erosion and deposition by wind, erosion and deposition through the action of liquid water in Mars' ancient past, freeze/thaw weathering and chemical weathering e.g. from the interaction of cosmic rays with the surface. Whilst the physical characteristic of the regolith is variable in terms of grain size and cohesion, measurements from the different Mars landers show that the composition is very similar in the different locations measured, which is thought to be suggestive of a global homogenising process. The chemical composition is dominantly 'basaltic' i.e. rich in the elements Si, Fe, Al, Mg, Ca along with O, S and some Cl [Gellert et al., 2004; Golombek et al., 2008].

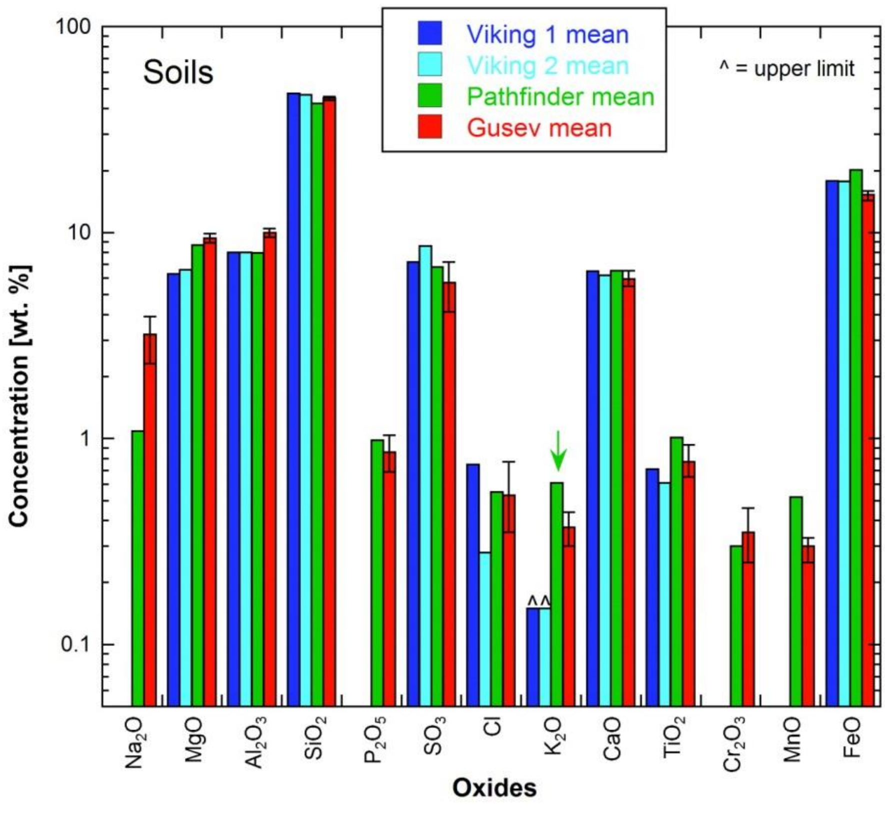

Fig. 8. Composition of soils measured by different lander missions show remarkable similarity in composition despite being in different locations on the Martian surface (taken from Gellert at al., 2004).

Lunar Sample Return Missions

An ESA Lunar Lander mission was in early stages of development with a planned launch date of 2018, however this work was put on hold in 2012. The main goals of the suspended mission were to visit the south polar region of the Moon and prove ability in guidance and navigation systems to land the spacecraft safely on the lunar surface. Once on the surface, the lander would have made various measurements of the environment with the aim of evaluating conditions for potential human exploration.

Owing to increasing cooperation between ESA and the Russian Federal Space Agency (Roscosmos) there is potential ESA involvement in a number of lunar exploration missions in the next few years as well as the re-invigoration of NASA lunar missions such as the proposed MoonRise mission (http://congrexprojects.com/2014-events/14c05a/introduction; ESA Workshop Report http://www.lpi.usra.edu/lunar/strategies/WorkshopOutcomesRecommendations033114.pdf; MoonRise presentation slides https://solarsystem.nasa.gov/docs/pr516.pdf).

The scientific objectives and mission architecture of the Russian Luna-25 and Luna-27 missions taken from Russian Spaceweb – Luna 25 Luna-Glob mission information (http://www.russianspaceweb.com/luna_glob_2013.html), Russian Spaceweb – Luna 27 Luna-Resurs mission information (http://www.russianspaceweb.com/luna_resurs.html) and the proposed NASA MoonRise mission will be used as a basis for starting assumptions.

ESA/ROSCOSMOS Luna 25 and Luna 27

The Luna 25 mission is due to launch in 2016 and land at the south polar region of the Moon and the Luna 27 mission is due to launch in 2019 and also visit the south polar region. Luna 27 has a potential scientific payload contribution from India.

The main scientific payloads include instruments designed to:

- Analyse the composition of the lunar regolith including searching for traces of water
- Map the lunar surface in terms of elemental composition and to study the surface to a depth of a few tens of meters to search for different constituents e.g. water ice
- Map the mineralogy of the moon including for hydrous phases
- Study the lunar exosphere
- Image the surface for 3-dimensional mapping.

On the landers there will be instruments for carrying determining chemical and elemental compositions and it appears from images of the proposed Luna 25 lander that there is a drilling mechanism to drill into the lunar surface, although it is not known to what depth. Presumably these drilled samples will be taken into the lander body and analysed using a variety of scientific instruments. It is assumed that these instruments will include those designed to provide chemical compositional information, including volatile element analyses to search for possible water ice.

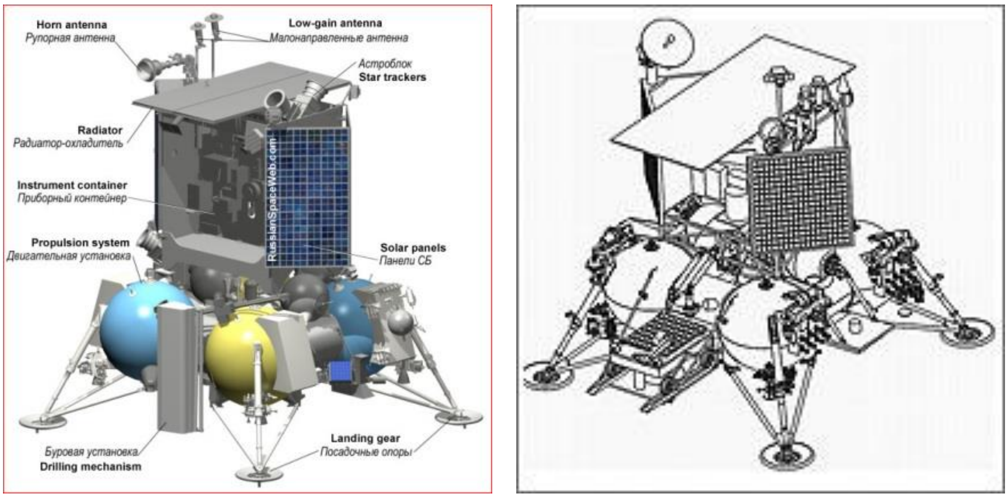

Fig. 9. Left, Luna 25 (Luna Glob) and right, Luna 27 (Luna Resurs) Taken from RD53 and RD54. Note the similarity of design although Luna 27 has the added rover.

Both the Luna 25 and Luna 27 missions will land and stay on the Moon's surface (duration TBD) to carry out a variety of scientific experiments. The Luna 27 mission is an enhanced design of the Lunar 25 lander with a larger scientific payload, a rover and, depending on the degree of European involvement, the capability to drill down into the lunar regolith up to a depth of 2m to search for water ice. This drill would be an adapted design from that on the ExoMars rover.

Possible landing sites for Luna 25 and Luna 27 have already been proposed. The sites were selected on the basis of three important factors:

- Data from the Lunar Exploration Neutron Detector (LEND) instrument on NASA's Lunar Reconnaissance Orbiter mission suggested the presence of water ice below the surface
- The regions have to have reasonable illumination as the landers rely on solar energy for power generation
- The topography is relatively 'flat', avoiding large craters, heavily crated areas or areas of high elevation or areas with steep slopes (<10-15°).

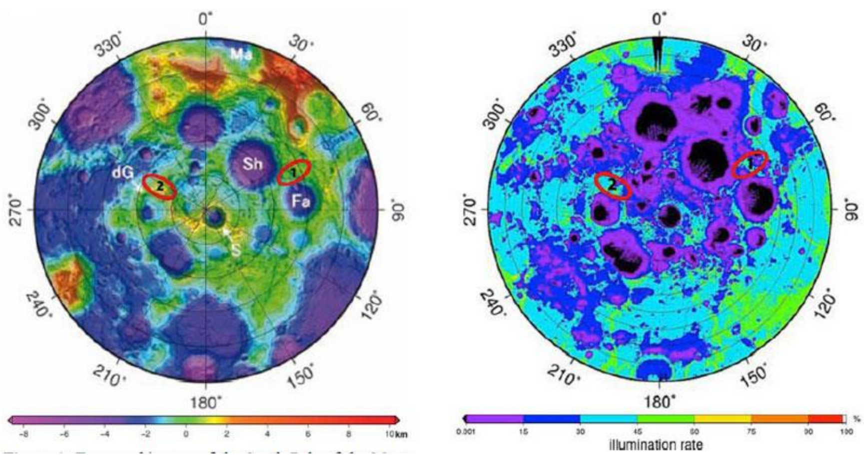

Fig. 10. Potential landing areas for Luna 24 and Luna 27 missions (from Slyuta et al.,2010).

NASA MoonRise

The proposed MoonRise mission would also target the South Pole Aitken Basin to collect ~1 kg of surface samples and was scheduled to launch and return samples to Earth in one year. The scientific objectives of the mission were:

- Determine the SPA Basin impact chronology
- Investigate processes associated with formation of large impact basins
- Investigate the materials excavated from the deeper crust and possibly the mantle of the Moon within the SPA Basin
- Determine the rock types and distribution of thorium and implications for the Moon's thermal evolution
- Sample and analyse basaltic rock and volcanic glass, which record the composition and chemical evolution of the Moon's far-side mantle beneath the SPA Basin.

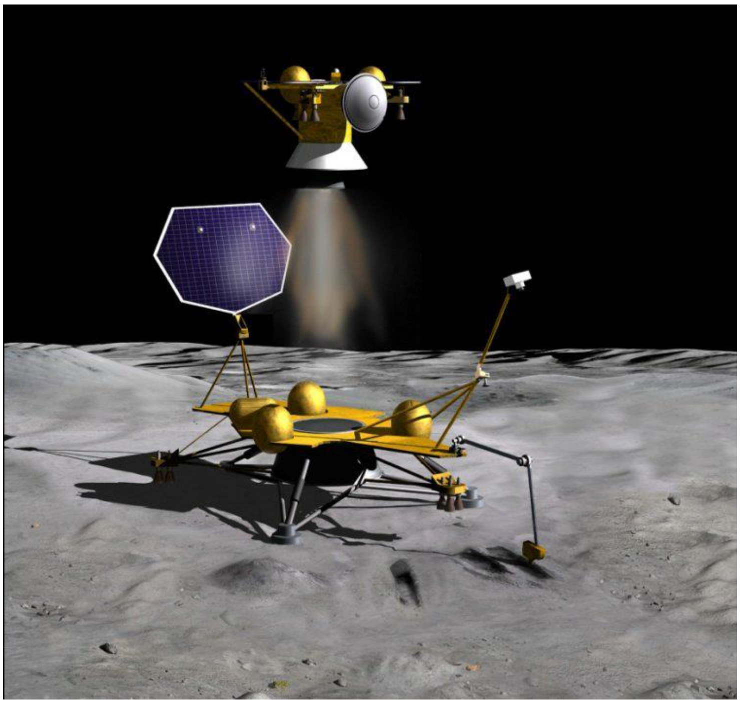

Fig. 11. Artist's impression of the MoonRise mission, note the sampling arm which would suggest that samples would be collected from the surface regolith and not from depth. Taken from https://solarsystem.nasa.gov/docs/pr516.pdf.

Moon Geological Context

It is important to note that our Moon has been extensively studied during humankind's exploration of the Solar System. So far, it is the only extra-terrestrial body on which humans have walked and have scientifically explored. There is a wealth of data and information on the geological history of the Moon, its composition and physical properties however given the aim of future exploration appears to be focussed on the south pole region and other regions where water ice may occur – water being seen as a critical resource for future human habitation and even for further exploration of our Solar System.

Previous sample return missions to the Moon (American Apollo and Russian Luna missions) have returned 100s of kilograms of surface samples; however these missions did not visit the southern polar regions. An additional challenge in determining the composition of the surface in the polar regions is the fact that these areas are often heavily shadowed and so it is difficult to obtain measurements through remote sensing by telescopes or orbiting spacecraft. However, it is reasonable to have as a starting assumption that the properties of the regolith in the south pole region will be mostly similar to those regions from where we do have samples, with the added potential for the presence of ices and higher volatile element abundances.

The lunar soil is a somewhat cohesive, dark grey to light grey, very-fine-grained, loose, clastic material derived primarily from the mechanical disintegration of basaltic and anorthositic rocks. The mean grain size of analysed soils ranges from about 40 µm to about 800 µm and averages between 60 and 80 µm. Individual lunar soil particles are mostly glass bonded aggregates (agglutinates) as well as various rock and mineral fragments. The soils range in composition from basaltic to anorthositic, and they include a small (<2%) meteoritic component. Although the chemical compositions of lunar soils show considerable variation, physical properties such as grain size, density, packing, and compressibility are rather uniform (McKay et al., 1991).

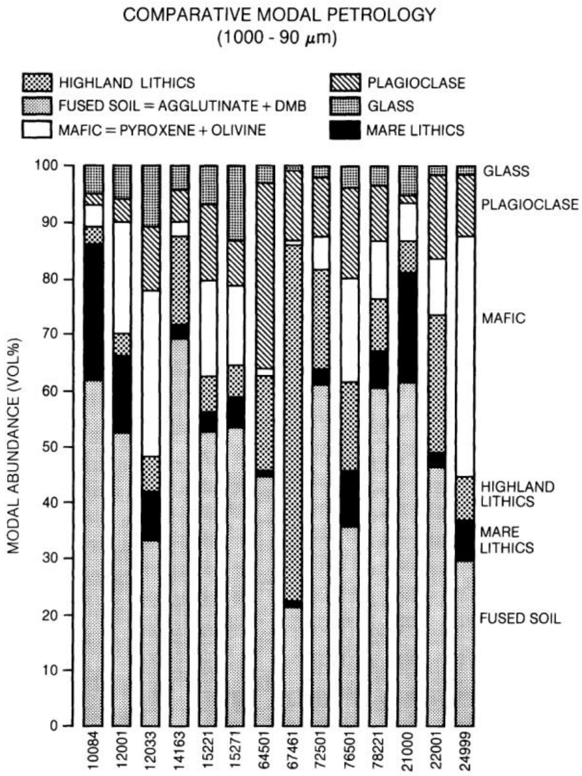

Fig.12. Modal abundances (vol %) of the different rock and mineral types found in lunar regolith (Taken from McKay et al. 1991)

Asteroid Sample Return Missions

There are no in-situ asteroid exploration missions currently under study by ESA. An asteroid sample return mission (MarcoPolo-R) was proposed and was under consideration as a potential mission being selected as a candidate for the M3 mission in the Cosmic Vision programme, however, it was ultimately not selected. JAXA and NASA do have asteroid sample return missions, which are currently in operation or about to be launched, and so the mission architecture for these missions is used to assess asteroid sample return missions.

JAXA Hayabusa 2

The Hayabusa 2 mission is an ambitious JAXA asteroid exploration mission launched in December 2014 and is due to arrive in 2018 at its C-type target asteroid 162173 Ryugyu (http://b612.jspec.jaxa.jp/hayabusa2/e/hayabusa2_sequence_e.html). After approximately 18 months of observations of the surface, the spacecraft will deploy two landers and also its sample collection mechanism will briefly touch down on the surface to collect surface material. A second sample collection phase will take place where a 2kg impactor will be fired at the asteroid surface with the aim of producing a crater a few metres wide (http://spaceflight101.com/spacecraft/hayabusa-2/). The spacecraft will make observations of the crater and the excavated material and will then touch down in the crater to collect the sub-surface material. If the mission follows the planned schedule, the Earth Return Capsule is due to return to Earth late 2020. Hayabusa 2 is a follow-on mission from technology demonstrator mission Hayabusa, which visited the S-type asteroid Itokawa in 2005 and collected samples from the surface (e.g. http://www.isas.jaxa.jp/e/enterp/missions/hayabusa/). The Hayabusa ERC returned in 2010, landing in the Australian desert; the samples it contained are still the focus of intense study by the international scientific community.

The main objectives of the Hayabusa 2 mission are:

- Visit a small asteroid whose orbit is similar to that of Itokawa, and aiming sample-return from an asteroid of different type from Itokawa
- The target body of Hayabusa 2 is a C-type asteroid, considered to contain more organic or hydrated materials than S-type asteroids like Itokawa
- What types of organic materials exist in the solar system, and is there any relation to life on Earth?

It has not been possible to ascertain the mass of material to be collected by the Hayabusa 2 mission. Despite the 'failure' of the Hayabusa sample collector, 1000s of asteroid surface particles in the size range 1-100 µm were collected. Preliminary characterisation and curation is carried out at the JAXA/ISAS Extraterrestrial Sample Curation Centre (ESCuC) in Sagamihara, Tokyo, Japan. Whilst there are no planetary protection requirements for these samples, the curation and study of such small particles which must be kept free from terrestrial contamination has posed a number of significant challenges to the design and operation of the curatorial facility (Yada et al., 2014).

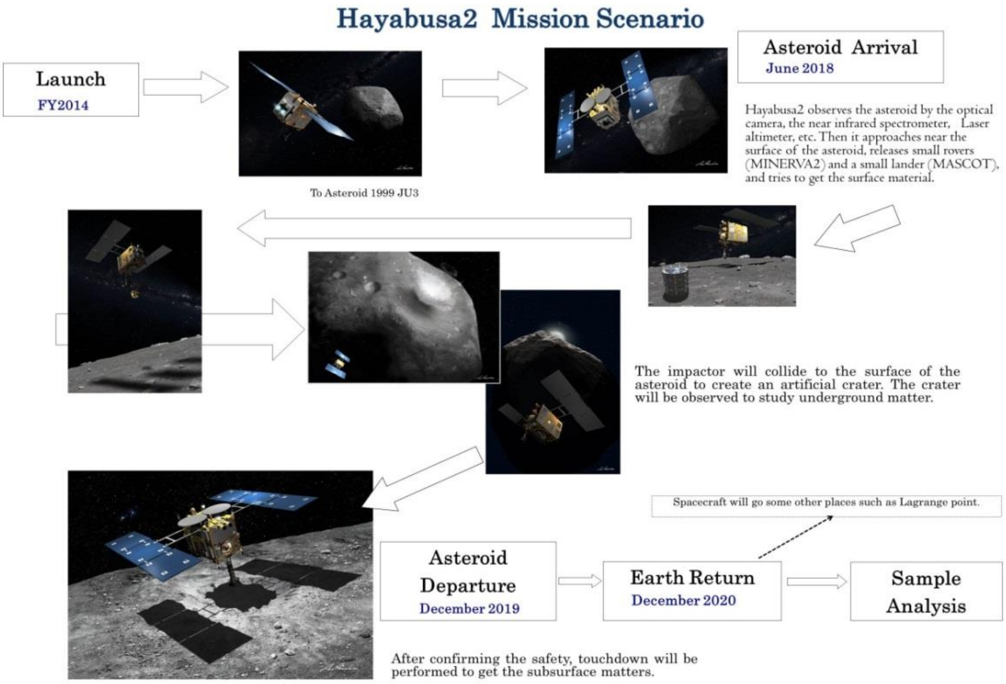

Fig. 13. Mission scenario for the Hayabusa 2 mission to asteroid Ryugyu.

NASA OSIRIS-REx

The NASA mission (OSIRIS-Rex) is due to launch in September 2016 and will travel to the B-type, Near Earth Asteroid Bennu, arriving in 2018 (note B-type asteroids are a sub-type of the large C-group). It will then spend 505 days carrying out detailed mapping of the asteroid's surface to understand the global properties, the mineralogy and chemistry. Once a suitable target site has been selected, the sample collector on the spacecraft will briefly touch down and collect at least 60g of sample, whilst also taking images of the surface. The spacecraft will leave the asteroid and the Earth Return Capsule is scheduled to land back on Earth in 2023 [http://www.asteroidmission.org/].

The mission objectives of the OSIRIS-Rex are:

- Return and analyse a sample of pristine carbonaceous asteroid regolith in an amount sufficient to study the nature, history, and distribution of its constituent minerals and organic material
- Map the global properties, chemistry, and mineralogy of a primitive carbonaceous asteroid to characterize its geologic and dynamic history and provide context for the returned samples
- Document the texture, morphology, geochemistry, and spectral properties of the regolith at the sampling site in situ at scales down to millimetres
- Measure the Yarkovsky effect, a thermal force on the object, on a potentially hazardous asteroid and constrain the asteroid properties that contribute to this effect
- Characterise the integrated global properties of a primitive carbonaceous asteroid to allow for direct comparison with ground-based telescopic data of the entire asteroid population.

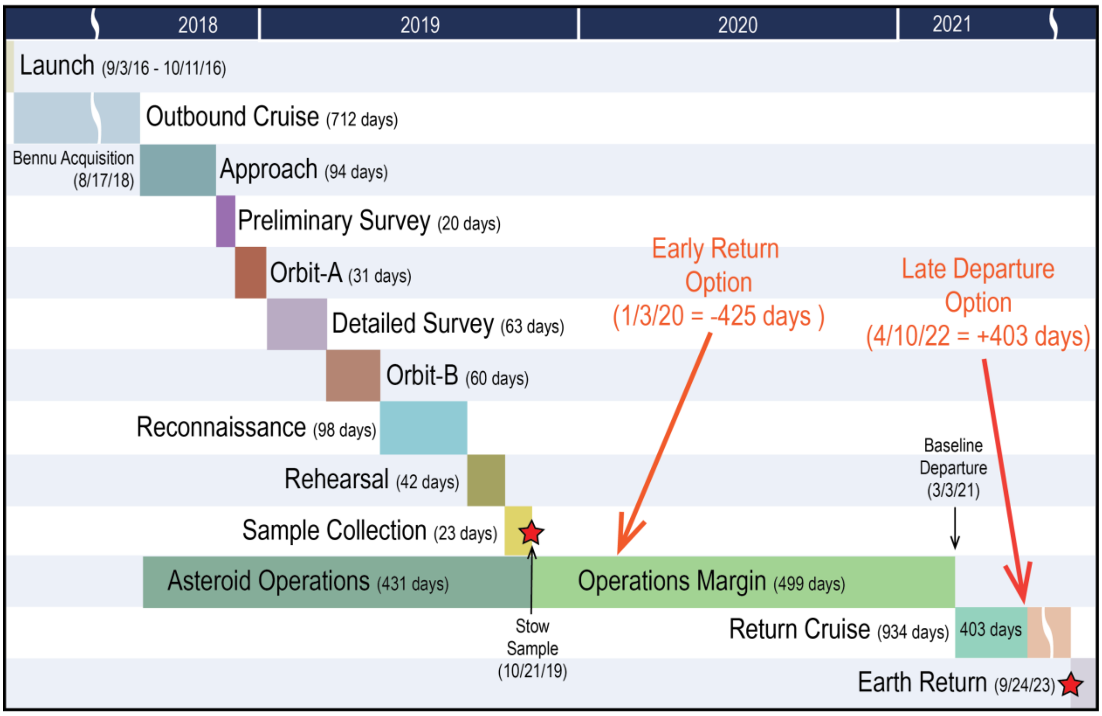

Fig. 14. OSIRIS-Rex mission timeline. From http://dslauretta.com/2015/02/08/the-osiris-rex-heavy-launch-opportunity/

Both Hayabusa 2 and OSIRIS-REx are 'touch and go' missions i.e. they do not physically land on the surface of the asteroid, rather their collecting mechanisms (called the TAGSAM on OSIRIS-REx) will briefly touch down on the surface, collect sample and then the spacecraft will move away.

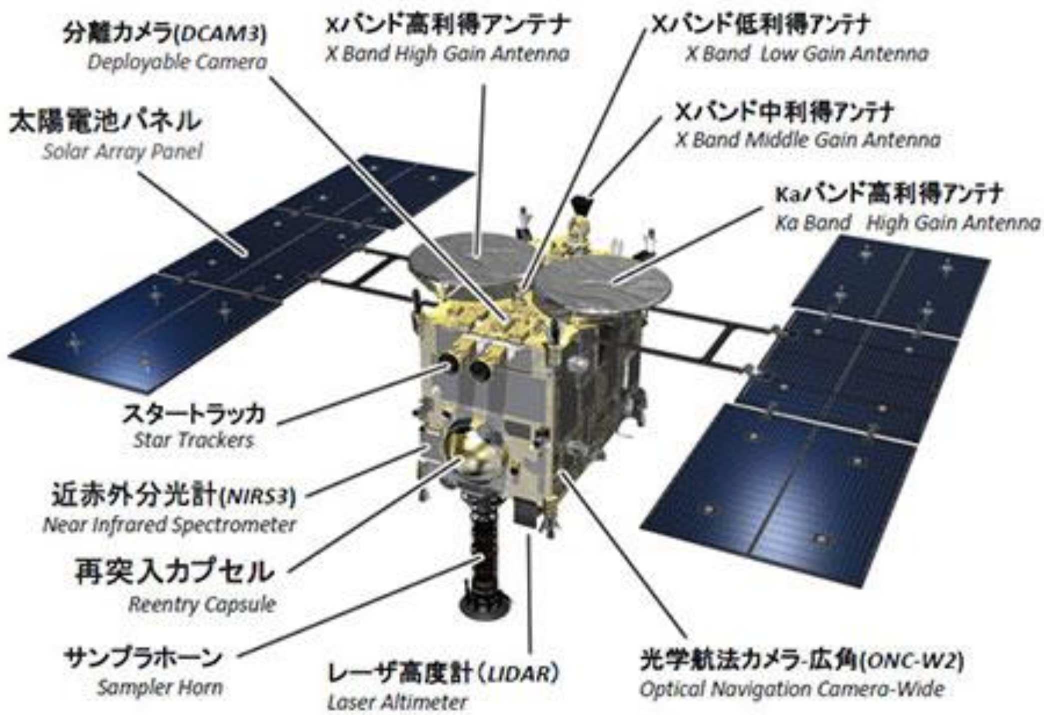

Fig. 15. Hayabusa 2 spacecraft showing instrument payload and sampling mechanism ('Sampler Horn'). From http://global.jaxa.jp/projects/sat/hayabusa2/index.html.

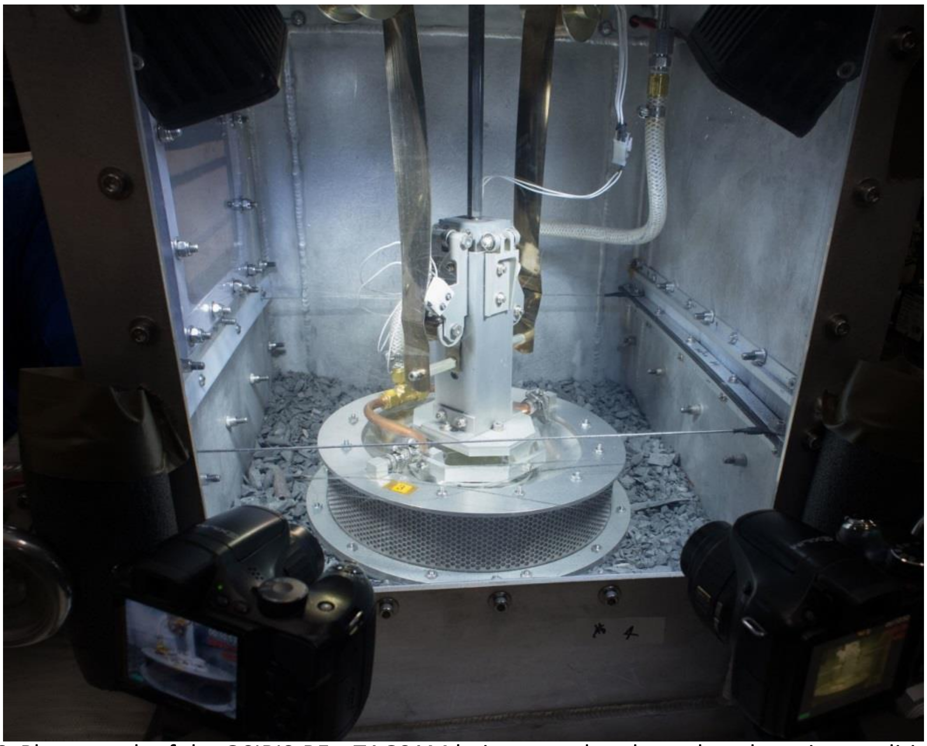

Fig. 16. Photograph of the OSIRIS-REx TAGSAM being tested under reduced gravity conditions. Image from http://dslauretta.com/2014/02/05/riding-the-vomit-comet/

Asteroid Geology Overview

Asteroids are rocky bodies orbiting the Sun that are too small to be classified as planets. Most asteroids orbit in the region between Mars and Jupiter (the so-called Asteroid Main Belt) although some have eccentric orbits that bring them close the Earth's orbit (near Earth objects, or NEOs) and others orbit around Jupiter or beyond. Asteroids are classified according to their spectral characteristics into families. There are two main taxonomic schemes currently in use in asteroid observational studies; the Tholen classification developed in the 1980s and the SMASSII-based classifications developed in the 1990s (Cellino et al., 2000).

The physical, mineralogical and chemical properties of asteroid surfaces can be determined through observations using ground-based and space-based telescopes and study by spacecraft. A number of spacecraft have made observations of asteroids either as a primary mission goal e.g. Hayabusa, NASA's NEAR Shoemaker and DAWN missions or as 'fly-by' where the mission is heading to another target body but passes close enough to an asteroid to make observation possible and scientifically worthwhile e.g. the observations of the asteroid Lutetia by ESA's Rosetta spacecraft in July 2010. Asteroids are diverse in their inferred compositions as determined by spectral signatures.

Asteroid Type/Class (SMASSI classification)	Inferred Composition	Meteorite Analogue	Inferred Bulk Density (g cm^{-3})
A-type	Pure olivine or a mixture of olivine and metal	?	
C-type (including B-type)	Phyllosilicates Olivine, pyroxene Opaque phases Organics Carbon	CM	Average 1.4
D-type	Phyllosilicates, olivine, pyroxene, opaque phases, carbon	Heated CM/CI Tagish Lake	Average 1.6
X-type	Pyroxene	Enstatite chondrites	
Q-type	Olivine, pyroxene, metal	?	
R-type	Olivine, pyroxene, possibly plagioclase.	HED?	
S-type	Olivine, pyroxene and metal	LL chondrite	Average 2.7
T-type	Unknown – possibly related to the D-types	CI/CM?	
V-type	Olivine, pyroxene, plagioclase	HEDs	Average 3.4
K-type	Olivine, pyroxene	CV/CO	

Table 1. Inferred compositions and corresponding meteorite analogues of the main types of asteroids. Data from Nelson et al. (1993) and Britt et al., (2002).

C-type asteroids are of greatest scientific interest as their spectral signatures indicate the presence of hydrated silicates, carbon, organic molecules and opaque minerals (magnetites and sulphides) and are considered to be amongst the most primitive materials in the Solar System. That is to say that they have undergone relatively little change since they formed within the protoplanetary disc approximately 4.6 billion years ago. The Hayabusa 2 mission is visiting a C-type asteroid and OSIRIS-REx mission is visiting a B-type asteroid. Laboratory-based studies have shown that the most similar analogues for these asteroids are the carbonaceous chondrite meteorites, and specifically the water-rich CI and CM chondrites (e.g. Beck et al., 2010).

Fig. 17. Image of the Ivuna CI chondrite (left) and the Murchison CM chondrite (right). The Ivuna sample is about 6 cm across and the Murchison sample is about 12 cm across.

High-resolution images of asteroid surfaces have been obtained by the NEAR Shoemaker spacecraft, which visited the asteroid Eros between 2000 and 2001. At the end of the mission, it was decided to attempt to land the spacecraft on the surface and in doing so to obtain some close-up images of the surface. Note Eros is an S-type asteroid, however it is assumed that its physical appearance will be at least similar to the C-type. Figure 18 clearly shows that the surface is made up of rocks and boulders ranging in size from a few metres to a few centimetres in size along with fine-grained material.

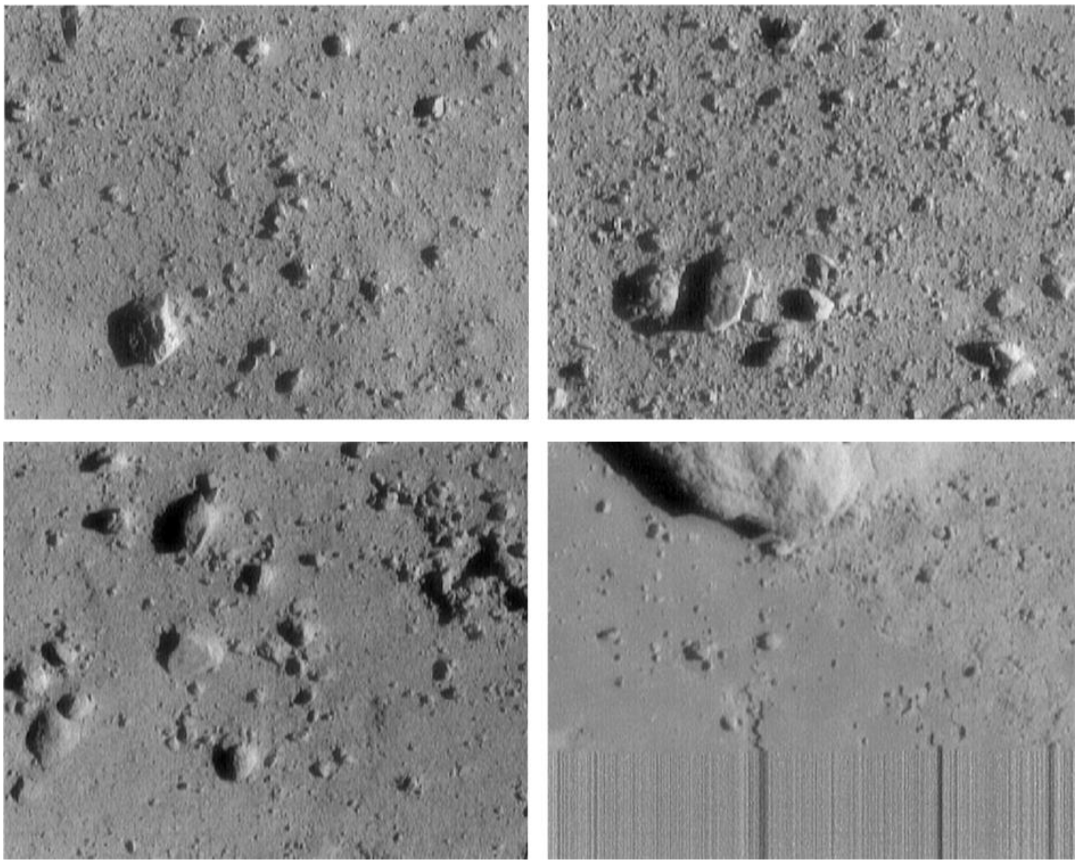

Fig. 18. Images of the surface of Eros taken by the NEAR-Shoemaker spacecraft just before it touched down on the surface. The top left image is 54 m wide, top right 33 m wide, bottom left 12 m wide and bottom right 6 m wide. The transmission of the last image was lost as the spacecraft touched down on the asteroid surface.

The Hayabusa spacecraft also visited an S-type asteroid (Itokawa) and took close-up images of the surface (Figure 19). The images show that the surface is complex in morphology with some areas being relatively rocky with rocks in the tens of centimetres to metres in size. The highest-resolution image shows a surface texture that is surprisingly ‘rubbly’, with little evidence of fine-grained material. In addition to the close-up images of the surface, the Hayabusa mission sampled, for the first time, surface material from an asteroid. The spacecraft collected ~1500 small particles, ranging between 3-40 µm in size, although the majority were < 10 µm. Most particles are angular and are thought to be fragments of broken rock. ~70% of the grains are monomineralic, with ~50 composed of olivine, ~17% pyroxene, ~17% feldspar, ~12 % troilite, and the remaining monomineralic grains being composed of chromite, Ca-phosphates and Fe-Ni metal. The other ~30% of grains are polymineralic grains and are composed of silicates (Nakamura et al., 2011)

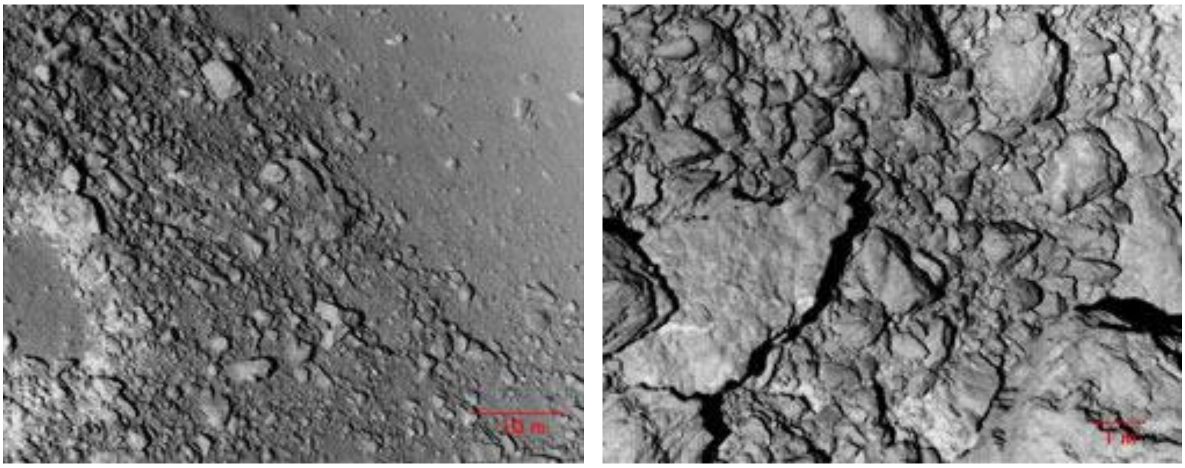

Fig. 19. Images showing the surface of Itokawa asteroid taken by the Hayabusa spacecraft. From http://www.jaxa.jp/press/2007/04/20070424_hayabusa_e.html

Although there are no high-resolution images or analyses of the surfaces of C-type asteroids, the physical properties of this type of material can be estimated from the properties of CI and CM chondrite specimens. Previous work on meteorite bulk density and porosity has shown that CI chondrites have a bulk density of ~1.6 g cm^{-3} with an average porosity of ~35 %, with CM chondrites having a bulk density of ~2.3 g cm^{-3} and an average porosity of ~23 % (Macke et al., 2011). These values are in agreement with calculations of the bulk densities of Phobos (~1. 6 g cm^{-3}) and for the 'average' C-type asteroid of ~1.4 g cm^{-3} (Britt et al., 2002). During handling and sub-sampling in a terrestrial, curatorial environment, both the CI and CM chondrites are typically quite friable, although can display significant variation from barely consolidated strong, well-consolidated samples.

Mars Moon (Phobos/Deimos) Sample Return Missions

The European Space Agency along with the Russian Space Agency have carried out a number of engineering and technology studies to investigate the feasibility of a potential Mars moon SR mission to Phobos and/or Deimos. These SR missions to Phobos/Deimos are part of ESA's MREP (Mars Robotic Exploration Preparation) program which "…is an Optional Programme being implemented in ESA's Directorate of Science and Robotic Exploration and intended to prepare Europe's future contribution to the international exploration of Mars." (http://www.esa.int/Our_Activities/Space_Engineering_Technology/Mars_Robotic_Exploration_Preparation_Programme_MREP). According to information available on the ESA website (http://sci.esa.int/sre-fmp/31586-sre-fmp-solar-system-and-robotic-exploration-missions-section/) there have been three Concurrent Design Facility (CDF) studies on Phobos/Deimos SR missions for the MREP programme:

- Phobos Sample Return (Phobos SR, CDF 2014)
- Mars Moon Sample Return (MMSR) – Ariane 5 launcher (CDF 2012)
- Mars Moon Sample Return (MMSR, CDF 2011)

And one industrial study – Mars Phobos Sample Return (PHOOTPRINT, 2014).

The CDF study (2014) for the Phobos Sample Return mission is available on the ESA website as a downloadable document (http://sci.esa.int/future-missions-office/55323-cdf-study-report-phobos-sample-return/), however the other three studies listed above do not appear to be freely available despite an extensive web search. Many of these studies are carried out in conjunction with industrial companies and so it is likely that commercially sensitive information is contained in these documents and hence are not publically available.

ESA Phobos Sample Return Mission

ESA Phobos Sample Return Mission CDF was carried out by an interdisciplinary team with the Russian Space Agency ROSCOSMOS to investigate the feasibility of a joint European/Russian Phobos Sample Return mission. The main mission requirements of relevance are:

- The mission shall return ~100 g of loose material from the surface of Phobos
- The mission shall be designed for launch in 2024 as a baseline, with 2026 as a backup.

The mission has two duration scenarios, one scenario of 2.7 years and the other of 4.8 years, and so assuming a launch in 2024 the Earth Return Capsule would land back on Earth in 2027 or 2029. Each scenario anticipates a period of 6 days of surface operations so, unlike for Hayabusa 2 and OSIRIS-REx, the spacecraft would land on the surface of the target body and stay there whilst sample acquisition and other surface science operations occurred.

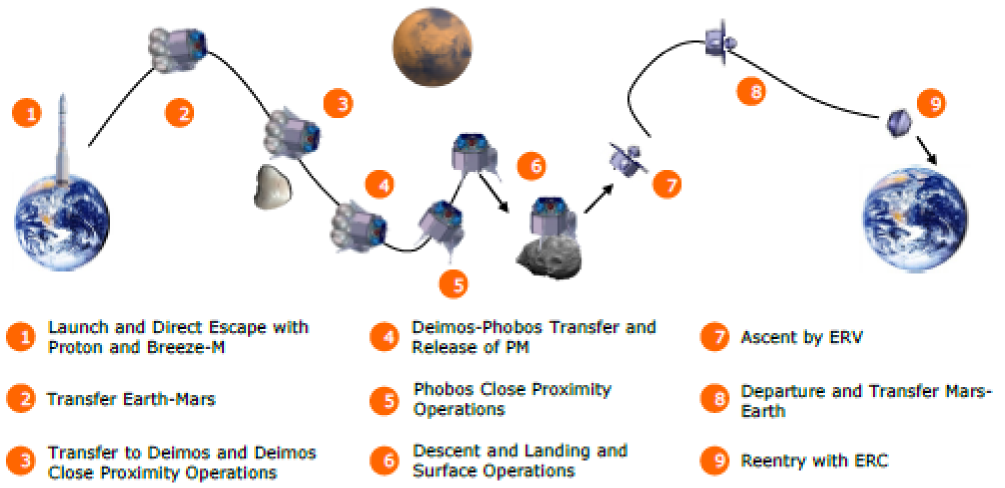

Fig. 20. Image of proposed mission architecture for a joint ESA/ROSCOSMOS Phobos SR mission. From ESA CDF study document http://sci.esa.int/future-missions-office/55323-cdf-study-report-phobos-sample-return/

The Russian Space Agency had its own Phobos SR mission 'Phobos-Grunt' which launched in November 2011, however failures in the rocket system of the launcher left the probe stranded in low Earth orbit and it the spacecraft crashed into the Pacific Ocean in January 2012.

Neither NASA or JAXA appear to have any 'formal' studies into a Mars moon SR mission, however, given both these agencies have current asteroid sample return missions it could be possible that the spacecraft/payload concepts could be repurposed for such an SR mission to Phobos or Deimos.

Phobos/Deimos Geology Overview

Observations of the Martian moons, Phobos and Deimos, indicate that they have a number of characteristics that are very similar to or even indistinguishable from D- type asteroids and so it is generally believed that these bodies are, in fact asteroids or perhaps even extinct comets that were captured early in Mars' history. Phobos is the larger moon, with a mean radius of 11.1 km, with Deimos being about half the size, with a mean radius of only 6.2 km.

There are at least two materials present on the surface of Phobos and Deimos that can be identified by different spectra signatures. Phobos displays a 'red' unit, which covers the majority of the moon and also a 'blue' unit, which is observed in the ejecta of the Stickney crater (note large crater on left hand side of Phobos in Figure 21 below). Deimos only shows the red spectral unit (Fraeman et al., 2013; Pieters et al., 2014).

Fig. 21. Phobos (left) and Deimos (right) as observed by the HiRISE instrument on Mars Reconnaissance Orbiter. (Taken from https://archive.org/details/TheScientificRationaleforRoboticExplorationofPhobosandDeimos)

The red unit of Phobos and Deimos shows a spectral absorption feature at 0.65 µm, indicative of the presence of Fe-bearing phyllosilicates or graphite and the overall spectra is very similar to that of the CM carbonaceous chondrites, suggesting that the compositions are very similar [Murchie et al., Fraeman et al., 2013; Pieters et al., 2014). There are also spectral similarities with the unique Tagish Lake meteorite which is classified as a CM or CI chondrites (Hiroi et al., 2001).

The blue unit is considered to be spectrally featureless and so it is difficult to compare with known compositions from other Solar System bodies. However, it is thought that it is a distinct unit and it is not simply that it is red unit material that has undergone changes through space weathering or other secondary processes. It is suggested that the blue unit may be distinct material which exists below the surface and is revealed by the large impact that resulted in the Stickney crater (Murchie et al., Fraeman et al., 2013; Pieters et al., 2014)

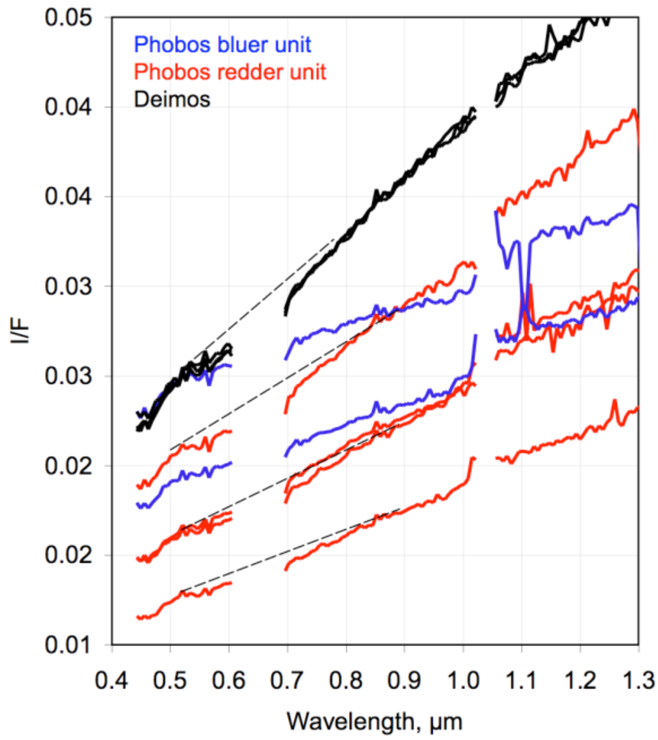

Fig. 22. Image showing spectral features of Phobos and Deimos from Murchie et al.

In summary, the majority of the surface of Phobos and the whole of Deimos are inferred to have the same composition, which is very similar to that of CM and CI chondrites.

The surfaces of Phobos and Deimos also show some differences. Phobos is heavily cratered and the large Stickney crater is a very obvious feature. Deimos' surface is much smoother with only a few craters visible, although it does have a large concavity in its southern half, which is inferred to be a very large impact crater. Indeed, this large impact, which was almost catastrophic, is suggested to have produced a 200m thick layer of impact ejecta, which forms the surface of Deimos and gives it its rounded shape (Pieters et al. 2014). The dynamical and orbital environment of Phobos and Deimos play an interesting part in the formation of the surface regolith whereby ejecta material formed by impacts will resettle on the surface in a period of ~10,000 years. Very small particles may be 'blown' onto the surface of the other moon by the effects of the solar wind. Space weathering and the interaction of cosmic rays with the surface is suggested to also play an important part in the regolith processing (Pieters et al., 2014).

Little is known about the physical properties of the regolith however some basic assumptions can be inferred by observations and modelling. The regolith is thought to be composed of fine grained, particulate matter. The fine grain size combined with the environment of the moons likely means that electrostatic forces are as important as gravity, adhesions and cohesion in terms of regolith formation and behaviour. Grains that are less than 10 µm in size can be lofted from the surface and be pushed away by the solar wind, whereas larger grains will fall back onto the moon's surface.

Target Body Future Sample Return Missions Summary

Solar System Body	Mission	Year of Launch	Year of Earth Return	Types of Sample	Amount of Sample
C-type Asteroid	JAXA Hayabusa 2	2014	2020	Surface regolith Sub-surface samples from crater created by impactor	Few grams (?)
C-type Asteroid	NASA OSIRIS-REx	2016	2023	Surface regolith	At least 60 g
Mars	NASA Mars2020	2020	TBC	Surface rock cores	~30 cores of ~15 g each
Mars	International Mars Sample Return	????? Mid 2020s	Likely 5 to 6 years post initial launch	TBD Likely surface regolith and sub-surface cores	~500g total
Lunar South Pole	ESA/ROSCOSMOS Lunar Lander	??????? 2016 and 2019	?????	Surface regolith and sub-surface cores. Sub-surface samples likely to contain volatiles	???? Likely a few grams to few hundreds of grams
Lunar South Pole	NASA MoonRISE	????	1 year after launch	Surface samples	~1 kg

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