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イトカワレゴリスの微細表面構造?LL コンドライトおよび衝突実験生成物との比較
Comparative analysis of surfaces of Itokawa regolith, LL chondrite and experimentally shocked olivine fragments

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探査機はやぶさはラブル・パイル構造を持つとされる S 型小惑星イトカワに到達し [1]、表面からレゴリス粒子を回収した。粒子の初期分析 [2-7] により、レゴリス粒子の多くは、熱変成を受けた LL5 もしくは LL6 コンドライトに類似する物質であることが明らかとなった [2-4]。また、粒子の 3 次元形状分析から衝突により形成された破片であり、一部の粒子表面が摩耗していることが示された [4]。また、粒子表面には、宇宙風化の痕跡 [6,7] やマイクロクレーター 8] などが報告されている。

これまでの分析において、イトカワ粒子の表面の微細構造観察はされていたが [8]、内部構造と比較した系統的な観察は行われていなかった。また、宇宙風化を受けていない LL コンドライトや衝撃実験生成物の表面観察との比較も重要である。そこで、本実験では、これらの粒子に対して走査型電子顕微鏡を用いた観察を行い、X線マイクロトモグラフィーによる分析結果 [9] を踏まえ、内部構造と表面との比較を試みた。

表面微細構造観察は電界放出走査型電子顕微鏡観察 (FE-SEM：JSM-7001F) を用いておこなった。サンプルは、イトカワレゴリス粒子 (A 室から採取された４粒子、B 室から採取された４粒子)、レゴリス粒子と同程度の大きさに砕いた Tuxtuac (LL5), Ensisheim (LL6) 隕石の破片である。また、衝突現象に由来する特徴を評価するため、大阪大学レーザーエネルギー学研究センターに設置された激光 XII 号を用いたカンラン石への衝撃実験の回収破片も観察した。衝撃圧力の最大値は約 38GPa である。比較のため、タングステン乳鉢を用いて砕いたカンラン石粒子も観察した。X 線マイクロトモグラフィーによる撮影はイトカワレゴリスおよび LL コンドライト粒子について、兵庫県にある大型放射光施設 SPring-8 の BL47XU にて行った [9]。

FE-SEM 観察の結果、レゴリス表面はおおまかに２つのタイプに分けることができた。１つは主に劈開ステップが観察される劈開面であり (タイプ 1)、もう１つは粒界で構成されている面である (タイプ 2)。タイプ１の表面は砕いたオリビン粒子、LL コンドライトにも見られた。この面は比較的大きな構成粒子 (カンラン石、輝石、斜長石) の劈開面からなる破断面である。一方、タイプ２に類似する表面は LL コンドライトでも見られ、これらは CT 像において比較的小さな構成粒子で構成されると考えられる破片に特徴的に見られた。イトカワレゴリス粒子においては、タイプ１、２の表面にかかわらず、鋭いエッジをもち摩耗などを受けていない新鮮な面（タイプ A）と、丸みを帯びたエッジをもち、表面が形成されてから比較的長時間が経過して摩耗を受けたと考えられる面（タイプ B）とに分けることができる。タイプ B の面はイトカワ粒子のみに確認された。丸みを帯びたエッジは、メテオロイド衝突によるイトカワの地震振動により誘起された機械的摩耗 [4]、もしくは宇宙風化 [6] により形成された可能性がある。またタイプ B の面には、高速度での衝突現象により形成された液滴が粒子表面に付着したような組織がしばしば観察された。衝撃実験から回収されたオリビン破片には、塑性変形を受け様々な方向へ伸びる多数のクラックを持つ粒子が観察されたが、このような粒子はレゴリス粒子、LL コンドライトにも存在しなかった。このような高い衝撃圧を受け生成された粒子は、衝突時にイトカワ表面から脱出している可能性がある。

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Keywords: Itokawa, regolith, LLchoondrite

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Shock state of the Itokawa samples
Shock state of the Itokawa samples

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Introduction: One of the fundamental aspects of any astro-material is its shock history [1]. The Hayabusa Preliminary Examination Team (HASPET) made shock stage determination of the Itokawa samples a primary goal [2]. The shock state of ordinary chondrite materials is generally determined by simple optical petrographic observation of standard thin sections, which we also did here. We made an additional estimation of the sample shock state by electron back-scattered diffraction (EBSD). We are also investigating the crystallinity of Itokawa olivine by synchrotron X-ray diffraction (SXRD).

Results: We made EBSD maps of 6 equilibrated (LL5/6) Itokawa. The EBSD maps revealed that olivine crystallinity varies considerably within the space of a few micrometers, and likewise albite, troilite and chromite. Albite was sometimes better crystalline than adjacent olivine, counter to our expectations. However, local variations in degree of crystallinity is a hallmark of shock metamorphism [1,4]. In order to determine the relative shock degree of the Itokawa grains we duplicated the EBSD analysis using grains from the Kilabo LL6 (shock stage S3) and Alfianello L6 (S5) ordinary chondrites. We used completely equilibrated type 6 chondrites in order to avoid potential complications from variable mineral compositions. By visually comparing the overall crystallinity of samples from EBSD and Band Slope maps we estimated that Itokawa samples should be assigned to be intermediate between Kilabo and Alfianello, therefore shock stage S4 by EBSD. We also determined the shock state of the Itokawa samples in the conventional manner under crossed polars in a standard petrographic microscope. Despite the irregular and non-standard specimen thickness this was surprisingly easy to do. We examined 29 separate grains. Practically all crystallites in the Itokawa grains exhibited minor to pronounced undulatory extinction. Some grains displayed distinct mosaicism. We saw no instances of shock veins in the equilibrated (LL5-6) grains, but there were amorphous regions in the unequilibrated LL4 grains. We observed no obvious parting or planar deformation features. Given the natural variability of shock effects [1] , these petrographic observations indicate shock stage S2, which is considerably lower than that suggested by the EBSD images (S4). To verify that shock levels were lower than S4 we have begun collecting SXRD data on larger Itokawa olivine grains. Grain RA-QD02-0049-2 consists almost entirely of olivine, and its diffraction pattern was very sharp, indicating insignificant shock metamorphism for this particular grain.

Conclusions: Shock effects can be effectively studied from even the tiny Itokawa grains, and by multiple techniques. It would be interesting to examine IDPs and lunar regolith grains in the same manner. However, EBSD and standard petrographic techniques are not equally sensitive to very fine-scale shock effects. EBSD appears to have greater potential to elucidate shock effects at the finest scale, but if EBSD data only are used to assign a shock stage these results may not be directly comparable to those obtained by standard petrographic techniques.

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顕微分光による ”はやぶさ ”微粒子の分析
A micro-spectroscopic research for the particles returned by the HAYABUSA mission

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Introduction: We have reported on micro-spectroscopic analyses of the particles returned by the HAYABUSA mission, in search of insoluble organic matter (IOM) [1-2]. It suggests to what extent thermal metamorphism has proceeded [3-7]. Five particles from the room A (RA-QD02-0017, 0033, 0044, 0049, and 0064) were analyzed by non-destructive methods; micro-Raman and IR techniques. The major Raman bands and IR absorptions can be assigned to olivine, and it seems the major mineral. Two particles from the room B (RB-QD04-0025 and RB-QD04-0049) were also analyzed in the same manner. The Raman spectra of RB-QD04-0049 showed that olivine is its major mineral, and the Raman bands of RB-QD04-0025 can be assigned to pyroxene and merrilite. However, the spectra lack in Raman bands or IR absorptions relating to carbonaceous matter. Although the seven particles may contain trace amount of low molecular weight organic compounds, there is no evidence for chondritic IOM [2]. In addition to the particles, we examined two particles by micro-Raman and IR techniques. And four particles were investigated by photoelectron emission microscopy (PEEM).

Methods: Two particles (RA-QD02-0008 and RB-QD04-0001) are analyzed by micro-Raman and IR in the same method using the newly designed sample holder made from diamond plates without using organic resin [1]. PEEM analyses were performed at the end-station of BL17SU in SPring-8. Four particles (RA-QD02-0010, RA-QD02-0031, RA-QD02-0068, and RB-QD04-0025) were analyzed using potted butt.

Results: RA-QD02-0008 and RB-QD04-0001 showed relatively strong fluorescence background at the Raman spectra. The IR spectrum of the particle RA-QD02-0008 is characterized by broad O-H stretching, however C-H stretching was not observed, unlike chondritic IOM. A PEEM image of the particle RA-QD02-0068 showed one carbon-rich phase in the particle.

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イトカワ粒子の宇宙風化産物の STEM 観察と N2 パージ環境の重要性
STEM observation of space weathering products on the Itokawa dust particles and importance of N2 purge environment

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Surfaces of airless bodies exposed to interplanetary space gradually have their structures, optical properties, chemical compositions, and mineralogy changed by solar wind implantation and sputtering, irradiation by galactic and solar cosmic rays, and micrometeorite bombardment. These alteration processes and the resultant optical changes are known as space weathering [1, 2, 3]. Our knowledge of space weathering has depended almost entirely on studies of the surface materials returned from the Moon and regolith breccia meteorites [1, 4, 5, 6]. Lunar soil studies show that space weathering darkens the albedo of lunar soil and regolith, reddens the slopes of their reflectance spectra, and attenuates the characteristic absorption bands of their reflectance spectra [1, 2, 3]. These changes are caused by vapor deposition of small (less than 40 nm) metallic Fe nanoparticles within the grain rims of lunar soils and agglutinates [5, 6, 7].

Structure of nanoparticle-bearing rims by the initial analysis of the Itokawa dust particles are as follows. Sulfur-bearing Fe-rich nanoparticles exist in a thin (5-15 nm) surface layer (zone I) on olivine, low-Ca pyroxene, and plagioclase, suggestive of vapor deposition. Sulfur-free npFe exist deeper inside (less than 60 nm) ferromagnesian silicates (zone II). Their texture suggests formation by amorphization and in-situ reduction of Fe2+ in ferromagnesian silicates [8]. On the other hand, nanophase metallic iron in the lunar samples is embedded in amorphous silicate [5, 6, 7]. These textural differences indicate that the major formation mechanisms of the metallic nanophase iron are different between the Itokawa and the lunar samples.

Eleven of them were embedded in epoxy resin and ultramicrotomed into about 100 nm-thick ultrathin sections. Four of them were preserved in N2 purge environment from the curation facility at ISAS/JAXA through ultramicrotomy at Ibaraki University to STEM observation at Hitachi high-technologies Co. Six samples were enclosed in thin (a few micrometer thick) epoxy resin at the curation facility to avoid long-haul exposure to the earth's atmosphere during experiments at Spring-8 and KEK-PF. Although these six samples ultramicrotomed in the earth's atmosphere, dehydrated ethylene glycol was used as trough liquid instead of distilled water to avoid unnecessary contact with water. Total exposure time to the earth's atmosphere was less than a few hours for these samples. One sample was kept in a desiccator for about one month at Osaka University, which means that it was kept in earth's atmosphere for a month. To evaluate the effect of long exposure to the earth's atmosphere, ultrathin sections were prepared for this sample by using the same procedures of the above six samples. All the samples were investigated using a spherical aberration corrected scanning transmission electron microscope to investigate space weathering products on the samples.

STEM observation of these particles revealed that some nanoparticle-bearing rims are vesiculated. Different from vesicular rims on the surface of lunar samples [5, 6], vesiculation occurred at the boundary between zone I and zone II or within zone II. We found that two samples without nanoparticle-bearing rims by have quite thin (2-3 nm) surface layers with elements that are not included in the substrate minerals, suggestive of vapor deposition from the surrounding minerals. We think that the quite thin layers are the immediate-early product of space weathering.

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はやぶさ回収試料の初期分析２:酸素同位体分析、微量元素分析
Preliminary examination of Hayabusa asteroidal samples: oxygen isotope and trace elements analyses

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Introduction: Oxygen isotopic compositions of asteroidal materials returned from Itokawa by the Hayabusa mission are all depleted in O-16 relative to terrestrial materials and indicate that Itokawa, an S-type asteroid, is one of the source of the LL or L group to equilibrated ordinary chondrites (Yurimoto et al., 2011). As the second round measurements, we measured, using secondary ion mass spectrometry, oxygen isotopic compositions and trace elements of individual minerals in 5 grains including poorly equilibrated particles from petrologic observations returned from Itokawa by the Hayabusa mission.

Experiments: Each grain was mounted at the center of an epoxy disk and the surface was polished under the processes established for the preliminary examination. The samples were gold-coated to a thickness of 60 nm.

Oxygen isotope compositions and trace element have been investigated by the Hokudai isotope microscope system (Cameca ims-1270 and 6f SIMS). The detail analytical conditions of oxygen isotope analyses are shown in Yurimoto et al. (2011). Trace elements analyses were performed by 6f SIMS in Hokudai. A 23keV O- primary ions is focused to ˜15micron on the sample surface and secondary ions were collected with EM. The detail analytical conditions were shown in Yurimoto et al. (1989).

Results and Discussion: All oxygen isotopic compositions of the minerals from Itokawa plot on the upper side of terrestrial materials on an oxygen three-isotope diagram and are distributed parallel to the terrestrial mass fractionation line. This result is consistent with those of L or LL chondrites. Even if some particles show the fractionated delta values (olivine) relative to those of other particles, the isotopic relationship among olivine, orthopyroxene and plagioclase shows that the oxygen isotopes fractionated under equilibrium between coexisting phases. On the basis of the small variation of D17OSMOW, the poorly equilibrated grains may have caused by late thermal process (e.g., shock melting) from the equilibrated grains made by thermal metamorphism like other Itokawa equilibrated grains. We measured trace elements of mesostasis parts in less equilibrium particles. Incompatible trace elements are enriched in the mesostasis. REE patterns are less fractionated among LREEs and HREEs.

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小惑星サンプルリターンミッション「はやぶさ２」の概要
Outline of the next asteroid sample return mission - Hayaubsa-2

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From 2011, Hayabusa follow-on mission, Hayabusa-2, has started. It is an asteroid sample return mission like Hayabusa, but the type of the target asteroid is C-type, which is different from the target of Hayabusa, Itokawa (S-type). It is considered that C-type asteroid contains more organic or hydrated minerals, so we can investigate the origin of water and organic matter of the life on the earth as well as the origin of the planets. The scale of the spacecraft is similar to Hayabusa, but many parts will be modified so that we will not have the troubles that we experienced in Hayabusa. Also the spacecraft has new equipment, which is called impactor. The impactor will make an artificial crater on the surface of the asteroid, and we will try to get the sample inside the crater. Then we can get much fresh material. The planned launch year is 2014 (2015 as backup), arriving at the target asteroid 1999 JU3 in 2018, and coming back to the earth 2020.

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はやぶさ２のサイエンスと科学観測機器
Hayabusa-2, scientific objective and instruments

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"Hayabusa2" is a successor asteroid sample-return mission of "Hayabusa" (MUSES-C), which proved several new technologies and returned to Earth in June 2010. While establishing a new navigation method using ion engines, Hayabusa succeeded in bringing back samples from the S-type asteroid "Itokawa". A C-type asteroid "1999 JU3" is a mission target of Hayabusa2 to solve the material changes accompanying evolution from primitive solar nebula to present asteroid, and to elucidate the formation and dynamical history of planetesimal and present asteroid. A C-type asteroid is a more primordial body than an S-type asteroid, and is considered to contain more organic or hydrated minerals. Minerals and seawater which form the Earth as well as materials for life are believed to be strongly connected in the primitive solar nebula in the early solar system, thus we expect to clarify the origin of life by analyzing samples acquired from a primordial celestial body such as a C-type asteroid to study organic matter and water in the solar system and how they coexist while affecting each other. The configuration of Hayabusa2 is basically the same as that of Hayabusa, but we will modify some parts by introducing novel technologies that evolved after the Hayabusa era. For example, a new function, "collision device", is considered to be onboard to create a crater artificially. An artificial crater that can be created by the device is expected to be a small one with a few meters in diameter, but still, by acquiring samples from the surface that is exposed by a collision, we can get fresh samples that are less weathered by the space environment or heat. Onboard scientific instruments are a near infrared spectrometer and mid infrared camera. Optical camera and laser altimeter which are carried for navigation guidance are also used for scientific objective. Small lander and/or rover are also planned to be carried. Hayabusa2 is scheduled for launch in 2014 (or 2015 as a backup.) It should arrive at the C-type asteroid in mid 2018, staying around there for one and half years before leaving the asteroid at the end of 2019 and returning to Earth around the end of 2020.

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Keywords: asteroid, sample return, remote sensing, exploration

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はやぶさ 2 リターンサンプルの科学
Science priorities for Hayabusa-2 return samples

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Recent progresses in research of extraterrestrial materials have revealed that the most pristine materials in the solar system are an interacted mixture of minerals, ice, and organic matter. However, there have been no returned samples keeping the interactions between inorganic materials, ice and organic matter intact. In this talk, we will illustrate the importance of sample-return return missions from undifferentiated primitive asteroids and comets, which preserve pristine minerals, ice, and organic materials, and introduce the scientific priorities for Hayabusa-2 return-samples from a C-type asteroid 1999 JU3.

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はやぶさ２搭載中間赤外カメラによる小惑星 1999JU3 の熱物性観測
Thermal Property of Asteroid 1999JU3 by Infrared Imager TIR on Hayabusa2

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A thermal infrared (TIR) imager is a nominal remote-sensing instrument onboard Hayabusa2, to investigate physical properties of the surface of C-class Near-Earth Asteroid 1999JU3. The instrument is based on the LIR (Long-InfraRed imager) onboard Akatsuki, a Japanese Venus climate orbiter to be inserted into Venus orbit in 2015 or 2016. Science objectives and current status of the instrument are briefly reported.

Hayabusa2 is the follow-on mission after the Japanese asteroid explorer Hayabusa and primarily an NEO (Near-Earth Object) sample-return mission, but remote sensing also has much importance to characterize global nature of the target body, which is complementary to analysis of returned samples. Since the target body is a C-class asteroid, optimal set of instruments is different from that of Hayabusa: telescopic (multi-band) imagers, laser ranger, near-infrared spectrometer to identify 3 micron absorption band, and a thermal infrared imager.

The original LIR instrument on Akatsuki has been developed for mapping Venus clouds at the temperature range of 220-250K. The instrument is applicable to mid-infrared imaging to investigate thermal inertia of asteroid surface. The instrument adopts a non-cooled bolometer array as its detector. The instrument has a field of view of 16 x 12 degree, detector of 320 x 240 effective pixels, and its targetted detection temperature range of 250 to 400K. The total mass is about 3.3 kg including the detector unit, hood, and electronics.

The main scientific missions are to investigate the global and local areal distribution of the surface physical properties. Surface physical properties are determined in 10 m spatial resolution from the Home Position 20km sunward from the asteroid. Higher resolved images are taken at lower altitude during the descent operation for touchdown. Thermal properties reflect the condition of materials, i.e. porosity of regolith or rocks, or particle size of soils. It will help understand the surface sedimentation processes under microgravity. Condition of large boulders or inner wall of huge craters informs the internal condition and alteration processes of parent body or current asteroid, respectively. Yarkovsky or YORP effects will be investigated by thermal imaging. TIR will also measure the properties of the surface geologic feature, crater ejecta, surrounding moons or floating dusts if they exist.

The TIR imager will also play an imprtant role for giving an information on sampling site selection by its surface physical condition as well as for assessing the spacecraft safety operation for touchdown by thermal emission or temperature.

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はやぶさ 2 LIDAR の科学目標
Scientific Objectives of Hayabusa-2 LIDAR experiment

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次期小惑星探査機「はやぶさ 2」に搭載されるレーザ距離計（LIDAR）の測定データを使った科学観測目標について講演する．小惑星探査の科学的意義を一言にまとめるならば,「原始惑星系円盤~微惑星~小惑星へといたる過程の missing piece を明らかにする」ということになるだろう．何故ならば，リターンサンプルは隕石と異なり産地情報を有しているので，サンプル分析結果をリモートセンシング観測と結びつけることで，サンプルが経験した「過程」を遡ることができるかも知れない．

第一の産地情報はすでに地上観測から得られている.「はやぶさ 2」の対象天体 1999JU3 についての軌道力学計算から，この小惑星はメインベルトの最内縁部から移動して
きた可能性が高いと考えられている．最内縁部の collisional family の中に C 型小惑星は少ないので，故郷の候補が絞り込みやすい．また，可視・近赤外での地上スペクトル観測からは，表面に大きな非均一を晒している可能性が示唆されている．もしもその場観察でそのような非均一が確認できれば，1999JU3 が経験したであろう衝突破壊の歴史を読み解く重要な鍵になり得る．

第二の産地情報は,「はやぶさ 2」のリモートセンシング観測データである．LIDAR は本来は光学航法のためのバス機器であるが，われわれサイエンスチームメンバーは距離測定から得られるデータの科学利用を検討している．LIDAR 観測の科学目標は,「衝突破壊・合体のプロセスを含めた小天体物理進化の謎解き」であり，具体的には下記の 3 つを掲げている．

(1) 1993JU3 の分光スペクトル観測（AMICA， NIRS3， アルベド）から，collisional family を同定する．

(2) 形状と重力から平均空隙率を計算し，rubble pile 天体の衝突破壊・合体の歴史を推定する．

(3) リターンサンプルの宇宙線照射年代，太陽風インプランテーション
から軌道進化を制約する．

加えて，Itokawa 探査の科学成果を発展させる（リターンサンプルをさらに活用する）ためにその場観察で何をすべきだったか？という観点から「はやぶさ」の観測計画を見なおした．そして，以下の 2 点を新たな科学目標に追加した．

(4) Rubble pile 天体を実証する．Itokawa と 1999JU3 の比較から，rubble pile 天体普遍性とバリエーション
を議論する．そのために，空隙率の均一 / 不均一性
を測定する．

(5) 小惑星ダストのその場観察を行う．はやぶさサンプルの出自は表層レゴリスであるのか，浮遊ダストであるのか,を確認する．小惑星周辺に漂う浮遊ダストを発見することができれば，空間密度分から，小惑星ダストの移流・攪拌をその場観察し (3) の解釈に反映する．

講演ではこれらの目標達成のために必要な観測機器性能を紹介し，観測感度や精度見積りを行う．また，観測は LIDAR データだけではなく，観測運用シナリオ，他機器（特にカメラ）との共同観測の設計が必要となる．現状の科学観測計画についても報告する．

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小型衝突装置 (SCI) からのサイエンス
Science from Small Carry-on Impactor

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小型衝突装置 (Small Carry on Impactor) は，はやぶさ２に搭載される機器の１つであり，1999JU3 表面のアクティブ探査に利用される．SCI は，直径 30cm ほどの円盤状の弾丸を持ち，この円盤は爆薬成形により，半球状の球殻弾丸として速度約 2km/s で JU3 表面に衝突する．この時形成される人工クレーター内部，もしくはその周囲から地下試料のサンプリングを可能にすることが SCI 搭載の第一の目的である．さらに，宇宙風化のない JU3 内部を暴露し，リモートセンシングにより宇宙風化の比較観測を可能にする．また，クレーター内部の観測なら浅層構造に関する知見を得ることも可能である．このような観測の成立性を検討するには，SCI により形成するクレーターの直径・深さや，掘削の深度を事前に知る必要がある．クレーター放出物に関する理論は，均質構造を持つ表層に関しては詳しく研究されており，特に砂などの非圧縮流を仮定できる物質に関しては，JU3 上に形成するクレーターの半径，放出物の最深点，堆積物の厚さを予測することができる．例えば，SCI で衝突させる 2kg の銅弾丸を仮定すると半径 5m，リムの厚さ約 1m，掘削物の最深点 1.2m のクレーターが形成されることになる．しかしながら，これらの理論を応用するには事前に表面状態を知っておく必要があり，JU3 のような未知の天体では，表面状態それ自身を調べることが探査の第一目標となる．さらに，JU3 のような微小天体では重力が極めて小さいので，クレーター形成理論の重力加速度に依存するメカニズムが重要な素過程となる．しかしながら，地上実験においては，微小重力下での実験は極めて難しいので既存の理論は実験においてその適応限界が確認されているわけではない．そこで，この SCI による人工クレーターの形成を小惑星上での衝突実験と位置づける．そして，この実験の目標はクレーター形成に関わる観測量から小惑星表面の物性を明らかにするのと同時に既存のクレータースケール則の検証と修正を行うこととする．

太陽系の形成過程を通して，天体衝突はその進化や多様化に重要な役割を果たしてきた．特に微惑星から小惑星母天体への衝突成長やその後の衝突破壊による小惑星の形成に関しては，衝突現象を理解することなしに，これらの結果形成された隕石や小惑星の多様性を理解することはできない．現在，我々は様々なタイプの小惑星を存在を確認しており，構造から分類すると，岩塊天体，均質多孔質天体，ラブルパイル天体などが典型的な例として挙げられる．天体の進化段階に従って，その構造は変化していくと思われるが，惑星形成過程の研究にはそれぞれの構造に対応した衝突のスケール則が必須であり，室内実験により現在も研究されている．一方，1999JU3 であるが，その構造は果たしてどのようなものであるかは，行ってみないとわからない．しかしがら，その内部構造や表面状態がどのようなものであっても，必ず，天体進化のある段階の構造を模擬したものであるとみなすことが可能である．我々は，ラブルパイル天体であるイトカワの表面を観測して，ガレ場，小石場，巨礫等の多様性に富んだ表層であることを発見した．同様な表面を JU3 に期待することが正しいかどうかはわからないが，どのような表面であれ，微小重力下という地球では得られない環境下で，模擬物質ではない本物の小惑星構成物質を利用した衝突実験を行うことができる価値は極めて高いと言える．

SCI を用いた衝突実験では，分離カメラ (DCAM) による衝突イジェクタのその場観測，ONC，TIR, NIRS3 による人工クレーターの観測を計画している．これらの観測を通して，クレータースケール則におけるイジェクタ速度やクレーター直径に対する物質依存性，重力加速度依存性に関する検証と改訂を行う予定である．この改訂作業を行うことは，同時に衝突地域の JU3 表面物性やその地下構造を決定することにもなるが，実際には，この実験結果をレファレンスとして，地上実験や数値シミュレーションとの連携により，さらに詳細な研究を行なっていく必要がある．SCI サイエンスチームでは，Small Carry-on Impactor Elucidates the Nature of Craters and Ejecta(SCIENCE) を合言葉に今後も SCI 成功のために検討を行なっていく予定である．

キーワード: 1999JU3, 衝突実験, 人工クレーター, クレータースケール則, 宇宙風化
Keywords: 1999JU3, Impact experiment, Artificial impact crater, Crater scaling law, Space weathering

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コンドライトへの弾丸衝突とエジェクタ回収実験
Laboratory Experiments of Impact onto Chondrites and Ejecta Recovery

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惑星間空間からの固体の高速度衝突は、小惑星表面にクレーターを形成し、ボルダーを破壊し、レゴリスを撹拌し、表面の物質を変性させる。このような衝突で小惑星から生じた破片は、惑星間空間の固体物質の主たるものとなる。そして、これらは、また小天体へ衝突する可能性を持つ。岩石やその他の小天体模擬物質を用いた衝突実験は過去に多く行われてきた。それに比べて隕石を用いた衝突実験はほとんど行われていない。マーチソン隕石を標的として、速度 4.45 km/s のアルミニウム弾丸を衝突させた過去実験では、数百ミクロンの大きさの破片が、無水隕石の場合に比べて多いという報告がなされている（Flynn et al. 2009）。

レーザーアブレーション法による弾丸加速は、小さな弾丸をガス銃に比べて良い精度で標的に衝突させられるため、量が限られる隕石の衝突実験を行うのに適している。そこで、われわれは、大阪大学レーザーエネルギー学研究センターの激光 XII HIPER レーザーを用いてレーザーアブレーションで弾丸を加速し（Kadono et al. 2010）、隕石に衝突させる実験を行った。標的は、LL5 コンドライト、アエンデ隕石、マーチソン隕石で、弾丸は直径 80 − 242 ミクロンのアルミニウム球、衝突速度は、10.7 から 43.9 km/s であった。我々はターゲット近くにエアロジェルを置き、破片を捕集した。衝突速度によらず、マーチソン隕石標的には深いクレーターができ、一方、LL5 コンドライト標的には非常に浅い不規則な形のくぼみができた。破片のサイズ分布についての予備的な結果についても示す。

キーワード: 衝突, 小惑星, エジェクタ, 塵, クレーター
Keywords: impact, asteroid, ejecta, dust, crater

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MarcoPolo-R: Asteroid Sample Return Mission
MarcoPolo-R: Asteroid Sample Return Mission

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MarcoPolo-R is a sample return mission to a primitive Near-Earth Asteroid (NEA) selected for an assessment study at ESA in the framework of ESA Cosmic Vision 2 program. The assessment study started at ESA on May 2011 and will continue until the middle of 2013. MarcoPolo-R is a European-led mission with a proposed NASA contribution. MarcoPolo-R will rendezvous with a primitive NEA, scientifically characterize it at multiple scales, and return a unique sample to Earth unaltered by the atmospheric entry process or terrestrial weathering. This project is based on the previous Marco Polo mission study, which was selected for the Assessment Phase of the first round of Cosmic Vision. Its scientific rationale was highly ranked by ESA committees, and it was not selected to proceed to the next step because the estimated cost was higher than the allotted amount for an M-class mission. The aim of the new Assessment Study is to reduce the cost of the mission while maintaining its high science level, on the basis of advanced studies and technologies, optimization of the mission, and consolidation of the collaboration with other partners.

The baseline target is a binary asteroid (175706) 1996 FG3, which offers a very efficient operational and technical mission profile. A binary target also provides enhanced science return. The choice of this target will allow new investigations to be performed more easily than at a single object, and also enables investigations of the fascinating geology and geophysics of asteroids that are impossible at a single object. Several launch windows have been identified in the time-span 2020-2024. The baseline mission scenario of MarcoPolo-R to 1996 FG3 is as follows: A single primary spacecraft, carrying the Earth re-entry capsule and sample acquisition and transfer system, will be launched by a Soyuz-Fregat rocket from Kourou.

The scientific payload includes state-of-the-art instruments, e.g. a camera system for high resolution imaging from orbit and on the surface, spectrometers covering visible, near-infrared and mid-infrared wavelengths, a neutral-particle analyser, a radio science experiment and optional laser altimeter. If resources are available, an optional Lander will be added to perform in-situ characterization close to the sampling site, and internal structure investigations.

MarcoPolo-R will return bulk samples from an organic-rich binary asteroid to Earth for laboratory analyses, allowing us to:
* explore the origin of planetary materials and initial stages of habitable planet formation;
* identify and characterize the organics and volatiles in a primitive asteroid;
* understand the unique geophysics, dynamics and evolution of a binary NEA.

In addition to addressing the exciting science goals, the MarcoPolo-R mission also involves technologies for which technical development programmes are well under way. It is the ideal platform to (i) demonstrate innovative capabilities such as: accurate planetary navigation and landing, sample return operational chain; (ii) prepare the next generation of curation facilities for extra-terrestrial sample storage and analysis; (iii) develop high-speed re-entry capsule; (iv) pave the way as a pathfinder mission for future sample returns from bodies with high surface gravity.

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HUMAN MISSIONS TO NEAR-EARTH ASTEROIDS: AN UPDATE ON NASA'S CURRENT STATUS AND PROPOSED ACTIVITIES

HUMAN MISSIONS TO NEAR-EARTH ASTEROIDS: AN UPDATE ON NASA'S CURRENT STATUS AND PROPOSED ACTIVITIES

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Introduction: Over the past several years, much attention has been focused on the human exploration of near-Earth asteroids (NEAs). Two independent NASA studies examined the feasibility of sending piloted missions to NEAs, and in 2009, the Augustine Commission identified NEAs as high profile destinations for human exploration missions beyond the Earth-Moon system as part of the Flexible Path. More recently the current U.S. presidential administration directed NASA to include NEAs as destinations for future human exploration with the goal of sending astronauts to a NEA in the mid to late 2020s. This directive became part of the official National Space Policy of the United States of America as of June 28, 2010.

Dynamical Assessment: The current near-term NASA human spaceflight capability is in the process of being defined while the Multi-Purpose Crew Vehicle (MPCV) and Space Launch System (SLS) are still in development. Hence, those NEAs in more accessible heliocentric orbits relative to a minimal interplanetary exploration capability will be considered for the first missions. If total mission durations for the first voyages to NEAs are to be kept to less than one year, with minimal velocity changes, then NEA rendezvous missions ideally will take place within 0.1 AU of Earth (˜15 million km or 37 lunar distances).

Human Exploration Considerations: These missions would be the first human expeditions to interplanetary bodies beyond the Earth-Moon system and would prove useful for testing technologies required for human missions to Mars, Phobos and Deimos, and other Solar System destinations. Missions to NEAs would undoubtedly provide a great deal of technical and engineering data on spacecraft operations for future human space exploration while conducting detailed scientific investigations of these primitive objects. Current analyses of operational concepts suggest that stay times of 15 to 30 days may be possible at these destinations. In addition, the resulting scientific investigations would refine designs for future extraterrestrial In Situ Resource Utilization (ISRU), and assist in the development of hazard mitigation techniques for planetary defense.

Conclusions: The scientific and hazard mitigation benefits, along with the programmatic and operational benefits of a human venture beyond the Earth-Moon system, make a piloted mission to a NEA using NASA's proposed human exploration systems a compelling endeavor.