Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

PCG32-01 会場:101B 時間:5 月 20 日 09:00-09:15

太陽系形成の標準シナリオとその課題
The standard scenario of solar system formation and its problems

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The solar system consists of planets, their satellites and rings, and a huge number of minor bodies. The planets can be classified into three groups: terrestrial planets (Mercury, Venus, Earth and Mars), gas giants (Jupiter and Saturn), and ice giants (Uranus and Neptune). These groups differ from one another by compositions, masses, and orbital radii. The terrestrial planets are light rocky ones with relatively small orbital radii, the gas giants are heavy planets with main components of hydrogen and helium gas in the middle of the solar system, and the ice giants are moderately massive with main components of water, methane, and ammonia ice in distant regions. These planetary orbits are nearly circular and coplanar, which suggests that the solar system was formed from a protoplanetary disk around the proto-sun.

The basic framework of the standard scenario for solar system formation was established in 1960's to 1980's. In the standard scenario, the solar system forms from a protoplanetary disk around the proto-sun that is a by-product of star formation and consists of gas and dust. The formation scenario can be divided into three stages: (1) formation of planetesimals from dust, (2) formation of protoplanets from planetesimals, and (3) formation of planets from protoplanets. In stage (1), planetesimals form from dust in the protoplanetary disk. Planetesimals are small building blocks of solid planets. Planetesimals grow by mutual collisions to protoplanets or planetary embryos in stage (2). The final stage (3) depends on a type of planets. The final stage of terrestrial planet formation is giant impacts among rocky protoplanets while sweeping residual planetesimals. Large protoplanets capture a massive gas envelope by self-gravity to become gas giant planets. Ice giants are leftover icy protoplanets that fail to become gas giants. Though the standard scenario can explain the formation of the basic structure of the solar system physically naturally, it has several serious unsolved problems such as planetesimal formation and timescale of giant planet formation. In the present talk, I review the basic elementary processes of solar system formation and discuss the problems now the standard scenario is facing.

キーワード: 太陽系, 惑星形成
Keywords: solar system, planet formation

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PCG32-02 会場:101B 時間:5 月 20 日 09:15-09:30

観測によって明らかとなった多様な系外惑星系の形成過程
Diverse formation mechanisms of exoplanetary systems revealed by observations

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近年の系外惑星観測によって、宇宙では多様な惑星系が形成されていることが明らかとなってきた。本講演では、（１）実際にどのような系外惑星系が発見されているのか、（２）その多様な惑星系がどのような条件のもとでどのように形成されるのか、の 2 点を中心に紹介する。

キーワード: 系外惑星
Keywords: Exoplanets

PCG32-03 会場:101B 時間:5 月 20 日 09:30-09:45

中間赤外線観測で探る温かいデブリ円盤
Warm Debris Disks Probed by Mid-Infrared Observations

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Some main-sequence stars are known to have dust disks around them, which should be composed of second-generation dust grains replenished during the main-sequence phase, rather than primordial dust from protoplanetary disks. These second-generation dust grains are thought to have originated in collisions of planetesimals or during the destruction of cometary objects, giving the reason circumstellar dust disks around main-sequence stars are named "debris disks." Debris disks are expected to be related to the stability of minor bodies and, potentially, to the presence of planets around stars. Debris disks are identified from the spectral energy distributions of stars that show an excess over their expected photospheric emission at infrared wavelengths, since circumstellar dust grains absorb the stellar light and re-emit mainly in the IR region. After the discovery of the first sample of debris disk, Vega, more than 100 others have been identified from the IRAS catalogue. Most of the known debris disks only show excess far-infrared emission. This excess comes from the thermal emission of dust grains with low temperatures, and is an analogue of Kuiper belt objects in the solar system. On the other hand, little is known to date about the warm debris disk material located close to the star, which should be an analogue of the asteroid belt in the solar system. Warm dust grains in the inner region of debris disks should have a more direct link to the formation of terrestrial planets than the low-temperature dust that has been previously studied.

To discover new warm debris disk candidates that show large 18 micron excess and estimate the fraction of stars with excess, we searched for point sources detected in the AKARI/IRC All-Sky Survey, which show a positional match with A-M dwarf stars in the Tycho-2 Spectral Type Catalogue and exhibit excess emission at 18 micron compared to expected photospheric level. In this presentation, we report initial results of the survey of warm debris disks around main-sequence stars based on the AKARI/IRC All-Sky Survey.

We also report the discovery of an intriguing debris disk toward the F3V star HD 15407A in which an extremely large amount of warm fine dust is detected. The dust temperature is derived as ~500-600 K and the location of the debris dust is estimated as 0.6-1.0 AU from the central star, a terrestrial planet region. The luminosity of the debris disk is ~0.5% of the stellar luminosity, which is much larger than those predicted by steady-state models of the debris disk produced by planetesimal collisions. The mid-infrared spectrum obtained by Spitzer indicates the presence of abundant micron-sized silica dust, suggesting that the dust comes from the surface layer of differentiated large rocky bodies.

キーワード: デブリ円盤, ダスト, 赤外線観測
Keywords: Debris Disks, Dust, Infrared Observations

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PCG32-04　　会場:101B　　時間:5 月 20 日 09:45-10:00

中間赤外線撮像観測から示唆される若い中質量星星周円盤構造進化
Evolution of disk structure around the young intermediate-mass star based on the mid-infrared

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我々は Subaru/COMICS および GeminiS/T-ReCS を用いて形成中の若い中質量星である Herbig Ae/Be 型星周りの星周円盤の 20um 帯の撮像サーベイを進めてきた。その結果、空間分解できた円盤には円盤中心領域にギャップ、または穴があることが分かってきた (e.g. Fujiwara et al. 2006, Honda et al. 2010, Honda et al. 2012, Maaskant et al. submitted)。このようなギャップや穴の存在は、多波長での観測からも示されてきており、ある種の円盤については内側領域の散逸が早く進んでいることが示唆される。一方でそのような構造を示さない円盤も存在しており、円盤進化の多様性が明らかとなってきた。以上の観測状況から示唆される星周円盤構造進化の描像について議論したい。

キーワード: 原始惑星系円盤
Keywords: protoplanetary disk

PCG32-05　　会場:101B　　時間:5 月 20 日 10:00-10:15

近赤外線直接観測で探る太陽型星に付随する原始惑星系円盤の形態進化
Probing the morphological evolution of circumstellar disks around solar-type stars with near-infrared direct imaging

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原始惑星系円盤は惑星形成の母体であると考えられており、惑星が円盤に埋もれている場合、円盤と惑星の重力相互作用によって面密度の小さな領域が円盤に形成されることが理論的に予想されている (e.g.,Zhu et al. 2011)。近年では天体のスペクトルエネルギー分布を詳しく解析した結果、近赤外線から中間赤外線にかけて赤外超過が減少している遷移円盤天体が報告されており (e.g., Strom et al. 1989)、さらに電波干渉計を用いた観測により空洞を持った円盤が観測されるなど (Andrews et al. 2011)、上記の天体に該当する可能性がある。

このように原始惑星系円盤の、特に半径 100 天文単位以内の領域は惑星形成と密接に関連していると考えられており、これまでに数多くの観測的研究がなされてきた。しかしながら、可視光や近赤外線を用いた撮像観測では、中心星が非常に明るいため半径 100 天文単位以内の惑星形成領域を直接観測することは非常に難しく (e.g., Grady et al. 1999)、また電波干渉計を用いた観測においても空間分解能が制限されているため (空間分解能 40 天文単位以上)、詳細な直接観測を行うことは困難であった (e.g., Andrews et al. 2011)。

そこで我々は、原始惑星系円盤の惑星形成領域 (半径 100 天文単位以内) を空間分解能 10 天文単位を切る高解像度で観測すべく、すばる望遠鏡に新しく高コントラストカメラ HiCIAO(ハイチャオ; Tamura et al. 2006) を開発した。HiCIAO には dual-beam 偏光器が搭載されており、従来の光・赤外線観測において障害となっていた明るい中心星の光を取り除くことが可能である。さらに補償光学装置と組み合わせることにより、高空間分解能を達成することが可能になる。

我々はこれまで、すばる望遠鏡戦略枠観測 SEEDS(Tamura 2009) の一環として、HiCIAO を用いた原始惑星系円盤の探査を行い、惑星形成がまさに進行していると考えられている遷移円盤天体の高解像度近赤外線偏光観測を集中して行ってきた。その結果、空間分解能 10 天文単位を達成し、惑星形成領域である円盤の半径 100 天文単位以内を観測することに成功し、これまでにおよそ 20 天体の遷移円盤を分解してきた。これらの遷移円盤を分類したところ、
(1)2 重リング構造が付随する天体、
(2) ギャップ構造が付随する天体、
(3) 近赤外線ではギャップ構造が検出できなかった天体、
という 3 つのカテゴリー分けることができた。
本講演ではこれまでの SEEDS 円盤観測を概観し、原始惑星系円盤がどのように惑星系へ進化するのか議論したい。

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PCG32-06 会場:101B 時間:5 月 20 日 10:15-10:30

局所 U-Pb 年代分析で紐解く太陽系年代学
New frontier of chronology of the Solar System based on in-situ U-Pb dating

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太陽系 46 億年の歴史において、天体と天体の衝突による惑星物質の角礫化は頻繁に起こった現象である。このような天体同士の衝突・破砕・角礫化が起こると、(i) 岩石試料は細粒化し、(ii) 放射壊変系が乱され、年代情報を引き出すことが技術的に難しい。しかし、リン酸塩鉱物中の 238U → 206Pb と 235U → 207Pb の 2 つの放射壊変系を精査することにより、母天体の結晶化年代のみならず衝突年代を導き出すことが原理的には可能である。本講演では、局所 U-Pb 年代分析の利点を解説するとともに、イオンマイクロプローブ (SHRIMP、NanoSIMS) による、熱変成・衝突・角礫化・再集積など複雑なプロセスを経験した普通コンドライト隕石の分析例について報告する。

キーワード: 年代分析, 太陽系, U-Pb 年代, 局所分析, 隕石, 同位体
Keywords: dating, Solar System, U-Pb age, in-situ analysis, meteorite, isotope

PCG32-07 会場:101B 時間:5 月 20 日 11:00-11:15

惑星表面のクレータ記録から探る太陽系進化史
Cratering chronology and evolution of the solar system

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惑星表面は過去 40 億年以上に及ぶ天体衝突の歴史をクレータとして記録している．本発表では月を中心とする固体天体表面のクレータ統計研究とそれから導かれる太陽系進化史に関する成果について紹介する．

キーワード: クレーター年代学
Keywords: cratering chronology

PCG32-08 会場:101B 時間:5 月 20 日 11:15-11:30

Northwest Africa 6704 のウラン－鉛年代学
U-Pb chronology of Northwest Africa 6704

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Northwest Africa (NWA) 6704 is a very unusual ungrouped fresh achondrite. It consists of abundant coarse-grained (up to 1.5 mm) low-Ca pyroxene, less abundant olivine, chromite, merrillite and interstitial sodic plagioclase. Minor minerals are awaruite, heazlewoodite, and pentlandite. Raman spectroscopy shows that a majority of the low-Ca pyroxene is orthopyroxene. Bulk major element abundances are nearly chondritic and distinct from those of howardite-eucrite-diogenites. Oxygen isotopic study demonstrated that 18O/16O and 17O/16O of this meteorite plot within the acapulcoite-lodranite field, but these meteorites differ in mineralogy and geochemistry. These observations suggest that NWA 6704 originated on a distinct parent body from all other known meteorites. Here we report U-Pb chronology of the unique achondrite NWA 6704.

U-Pb dating was performed on nine 10?20 mg fractions of pyroxene. All fractions were washed 4-5 times in ca. 0.5 ml of 0.5 M HNO3. Subsequently, the fractions were washed twice with hot 6 M HCl, followed by twice washing with hot 7 M HNO3. All residues were spiked with mixed 202Pb-205Pb-229Th-233U-236U tracer. Spiked residues were digested in a HF+HNO3 mixture, converted to a soluble form by repeated evaporation with 7 M HNO3, 6 M HCl, 9 M HBr, and dissolved in 0.3 M HBr. The Pb separation was performed using 0.05 ml of anion exchange resin AG1x8 200?400 mesh. After the Pb separation, U and Th were separated using 0.05 ml of UTEVA resin. Pb isotopes were measured on a TRITON Plus TIMS at the ANU. U and Th isotopic analyses were carried out on a Neptune MC-ICPMS at the Australian National University.

Two residues yielded higher 206Pb/204Pb values (148 and 213) relative to the others (from 344 to 5494). Model 207Pb*/206Pb* dates (assuming primordial Pb as initial Pb, and 238U/235U=137.88) for seven most radiogenic residue analyses with 206Pb/204Pb more than 500 yielded a weighted average of 4563.34 +/- 0.32 Ma. The U-Pb discordance of residue analyses range from -3% to -6% for more radiogenic data, and up to -10% for the two residues that contain less radiogenic Pb. A Pb-Pb isochron for the seven radiogenic residues yielded a radiogenic 207Pb/206Pb value (y-intercept of the regression line) of 0.62351+/-0.00017. This corresponds to a 207Pb/206Pb date of 4563.75 +/- 0.41 Ma, assuming a 238U/235U=137.88. Yet this assumption may be invalid likewise for Ca-Al-rich inclusions (CAIs) and basaltic achondrites. Hence, to establish an assumption-free reliable 207Pb/206Pb date, precise 238U/235U needs to be determined for this meteorite. Using, instead, the 238U/235U value of 137.79+/-0.02 (an approximate estimate for most Solar System materials except CAIs), yields the isochron age of 4562.80+/-0.46 Ma. This age estimate is valid unless 238U/235U in NWA 6704 is significantly lower than in the angrites and chondrites. Determination of the 238U/235U is in progress.

The estimated U-Pb age of NWA 6704 is substantially older than those of plutonic angrites, and only marginally younger than those of quenched angrites. NWA 6704 is about 4-5 Ma younger than the CAIs. Considering the old crystallization age, the expected simple geologic history (suggested by nearly concordant U-Pb systems), the mineral assemblage including pyroxene, plagioclase, olivine, chromite and metal, and the considerable sample size (8.4 kg in total), NWA 6704 has the potential to serve as a reliable reference point of various short-lived isotopic chronometers such as 26Al-26Mg, 53Mn-53Cr and 182Hf-182W chronometers. A new reliable reference point is essential for checking uniform distribution of the short-lived radionuclides and for building a consistent time scale of the early Solar System.

PCG32-09 会場:101B 時間:5 月 20 日 11:30-11:45

地球で一番古い石
The oldest rocks in the world

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The solar system was formed at 4.567 Ga; thus we can obtain the age from chondrules in a chondrite. On the other hand, it is well known that the earth was formed soon after the formation of the chondrites, but we cannot directly obtain the age of the formation of the earth from materials on the earth. So far, the oldest rock in the world goes back to 4.03 Ga, and occurs in the Acasta Gneiss Complex, Canada. The first five hundred million years of the history of the earth are still in dark. The Hadean from the formation of the earth to the oldest age of rocks or geologic bodies is the most mysterious period because no rocks and geologic bodies are preserved at present except for the Hadean zircons only in several terranes, Western Australia, Canada, China and Greenland [1]. But, the Hadean period is the most important because the early evolution in the Hadean possibly clinched the evolution of the earth. In order to investigate the Hadean tectonics, we try to find the earliest Archean geologic terranes in the world. So far, the oldest geologic terranes comprise Acasta Gneiss complex, Akilia association in the West Greenland, Nuvvuagittuq in Quebec, Canada, and Nain Complex in Labrador, Canada [2].

We made geological survey in the Nain Complex, and reinvestigated the occurrence of the supracrustal rocks and the relationship with the ambient orthogneisses. Because previous works focused on distribution of the supracrustal belts within the orthogneisses, the detailed field occurrence of the supracrustal rocks within the belts is still ambiguous. Therefore, we focus on their internal structures.

Although the supracrustal belts are repeatedly intruded by granitic intrusions with some ages and their original structures are obscured, their lithostratigraphies are relatively well preserved in Nulliak, Big and Shuldham islands and St Jones Harbor. The supracrustal belts in Nulliak Island and Big Island comprise ultramafic rocks, mafic rocks and mafic sediments intercalated with banded iron formations in ascending order. In the St. Jones Harbor, it is composed of ultramafic rocks, mafic rocks, banded iron formation, and clastic sediments, intercalated with chert in the middle and with bedded carbonate rocks in the upper part, in ascending order. In the Shuldham Island, it consists of ultramafic rocks, layered gabbro with precursors of plagioclase and pyroxene accumulation layers, mafic rocks and psammitic sediments in ascending order.

Recently, we found 3.956 Ma zircons from the Nanok Gneiss, intruding the supracrustal rocks in the St. Jones Harbor area [3]. So far, the host rock including the zircons is the second oldest rock in the world. Because no supracrustal rocks are found in the Acasta Gneiss Complex, the Nulliak supracrustal rocks are the oldest supracrustal rocks in the world. The discovery of the oldest supracrustal rocks opens the door to investigate the early evolution of the earth in the Hadean.

[1] Froude et al. (1983) Nature 304, 616-618; Nelson et al. (2000) EPSL 181, 89-102; Mojzsis & Harrison (2002) EPSL 202, 563-576; Iizuka et al. (2006) Geology 34, 245-248; Wang et al. (2007) CSB 52, 3002-3010. [2] Bowring & Williams (1999) CMP 134, 3-16; Nutman et al. (1996) Precamb. Res. 78, 1-39; O'Neil et al. (2008) Science 321, 1828-1831. [2] Shimojo et al. (2012) abstract for Goldschmidt Conference 2012.

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火星隕石ALH 84001中のリン酸塩鉱物のシングルグレインU-Pb年代分析：隕石の熱史の解明に向けて
Ion microprobe U-Pb dating of individual phosphate minerals in Martian meteorite: ALH 84001.

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Mizuho Koike[1*], OTA, Yoshihiro[1], Naoto Takahata[1], Yuji Sano[1], naoji sugiura[2]

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はじめに
火星は、その地表物質を地球に居ながらにして隕石というかたちで直接調べることの出来る、唯一の惑星である。現在までに多数の隕石が火星起源であることが確かめられて来た。中でもALH84001は非常に古い結晶化年代を示し、惑星の太古の環境を知る上で重要な情報を持つと期待される。一方で、隕石中に含まれるリン酸塩鉱物は、UやThなどの微量元素を濃集し年代分析に用いられる。先行研究ではALH84001のリン酸塩鉱物のU-Pb年代が~4 Gaと得られ、過去の衝撃イベントによる変成を示していると考えられた[1]。より微小な領域(グレイン内部の元素・同位体分布など)を解明することで、隕石の受けた化学的・物理的プロセスに新たな制約を与えることが可能である。本研究では、水平方向に高い空間分解能をもつNanoSIMSを用いて、ALH84001のリン酸塩のグレインごとのU-Pb年代を分析し、さらにこの隕石の熱史について考察した。

分析手法
今回使用したサンプルは、ALH84001の厚片試料2枚である。SEM-EDSにて観察し、各厚片から50-100ミクロンのリン酸塩グレインを発見した(Grain 1, Grain 2)。試料は再研磨後に金コーティングし、SIMS分析の前に一晩以上ベイクしている。SIMSの一次イオンビームには2-10nAのO^-イオンを用いた(スポットサイズ10-20ミクロン)。U-Pb分析のスタンダードには、年代が既知(1155 +/- 20 Ma, [2])カナダ産のアパタイト: PRAPが用いられた。

結果および考察
２つのリン酸塩グレインについて、それぞれ^{238}U-^{206}Pb年代および^{207}Pb-^{206}Pb年代を調べた。得られた４つの年代は全て~4 Gaで、グレイン内でU-Pb系がコンコーダントであることが示された。また、この結果は先行研究とも誤差の範囲で一致し、本手法では少ないサンプル消費量で正確な年代を得られることが示唆された。
更に、得られた年代が何を意味するのかについて考えるため、分析したグレインにおけるU-Pb系の閉鎖温度を計算した。冷却過程における閉鎖温度(T_c)は、冷却速度をT'として以下の式で近似される[3]:
$T_c=(E/R)/(\ln[ART_c^2(D_0/a^2)/ET'])$
ここで、Rは気体定数、Eは活性化エネルギー, D_0は拡散定数でアパタイトの鉛の値でそれぞれ55.3 kcal/mol、0.0002 cm^2/s[4]、Aは定数で55、aはグレインの半径50ミクロンとする。ALH84001は~4 Gaに衝撃イベントを経験し、その後炭酸塩鉱物を形成している[5]。炭酸塩の形成プロセスは未だにはっきりしていないが、炭酸塩中のCa-Mgの１ミクロンの濃度パターンから、(i) $<200\ ^oC$の低温でゆっくり(10^{-1} to $10^3\ ^oC/Ma$)形成したか、あるいは(ii) $>600\ ^oC$の高温から急冷されて($10^7\ ^oC/Ma$)形成したと考えられる[6]。分析したグレインのT_cは(i)の場合に~400-500 ^oC、(ii)の場合に$>800\ ^oC$となり、いずれの場合も周囲の温度が閉鎖温度を超えないことが示される。今回の結果では、炭酸塩生成より前のイベントでリン酸塩のU-Pb系がリセットされた可能性は残される。適切な解釈のためには更なる分析が必要であるが、本研究により、リン酸塩鉱物が隕石形成時の情報を保持し得ることが示唆された。

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キーワード: ウラン-鉛年代その場分析, 火星隕石, リン酸塩鉱物, 熱史
Keywords: in-situ U-Pb dating, Martian meteorite, phosphates, thermal history

PCG32-11 会場:101B 時間:5 月 20 日 12:00-12:15

Solar wind and cosmic-ray irradiation history of surface materials on small asteroid Itokawa

Solar wind and cosmic-ray irradiation history of surface materials on small asteroid Itokawa

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Surface materials of small asteroids are exposed to various energetic particles such as solar wind (SW), solar cosmic rays (SCRs), and galactic cosmic rays (GCRs). SW particles (with energy of ca. keV per nucleon) are implanted into thin layer, smaller than micro-m from the grain surface. SCRs are composed of more energetic solar particles (1-100 MeV per nucleon), whereas GCRs have even higher energies of larger than 0.1 GeV. The high energy protons from SCRs penetrate several centimeters, and GCRs penetrate up to 1 meter or more beneath the surface of asteroid. Nuclear reactions caused by these energetic cosmic rays can produce noble gases with characteristic isotopic compositions (cosmogenic noble gases) on their passages in solid materials. SW and cosmogenic noble gases can be easily identified because of their characteristic isotopic and elemental compositions [1-4].

The Hayabusa samples are pristine undamaged grains collected from the unconsolidated surface of small asteroid Itokawa with micro-gravity. The samples are essentially different from other extraterrestrial materials such as micrometeorites (MMs) and stratospheric interplanetary dust particles (IDPs) recovered on Earth. They have experienced frictional heating and ablation of the surface layer during passage through the atmosphere and have then suffered from contamination of terrestrial atmospheric noble gases [5, 6].

We have measured noble gases for three Hayabusa grains [7] as an initial investigation, and are continuing for additional Hayabusa samples as an international AO investigation (JAXA). They were olivine grains, and their sizes and weights were as small as 40-60 micro-meter (SEM observation) and 0.05-0.1 micro-gram (estimation from their shapes and density of olivine), respectively.

Variable amounts of light noble gases of SW origin were measured for the samples, which are clear evidences that the grains had been exposed directly to SW particles on the uppermost surface of Itokawa. The detection of SW noble gases is relatively easy because of the high fluxes of SW-light noble gases (He, Ne and Ar). Observed abundances of SW gases in the samples could be accumulated if they were exposed to SW particles for 100-1000 years [7].

On the contrary, cosmogenic noble gas isotopes were difficult to be detected for these tiny samples. Fluxes of SCR and GCR are much smaller than those of SW, and production rates of cosmogenic isotopes are very small, i.e., estimated production rate by GCR in a single grain weighing 0.1 micro-g is as small as 3500 atoms /My. Even in the case, we can give an upper limit to the time span of cosmic-ray irradiation (cosmic-ray exposure age) for each grain. Combining the production of ^{21}Ne by SCR and GCR [8] we obtained 8 My as an upper limit for the RA-QD02-0065 sample [7]. These data can provide unique chronological information about the grains in surface layer of small asteroids.

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Keywords: Solar wind, Cosmic ray, irradiation history, Itokawa, Hayabusa

Japan Geoscience Union Meeting 2013
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PCG32-12 会場:101B 時間:5 月 20 日 12:15-12:30

惑星探査における K-Ar 年代のその場計測
A K-Ar dating instrument for future in-situ dating on planetary surfaces

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Surface retention age is one of the most fundamental observables in planetary science. Crater chronology is often used to estimate the timing of geologic events. For example, crater counting on lunar maria revealed most of the mare basalts were emplaced 3.5 Gyr ago, while the latest eruptions occurred 1-2 Gyr ago mainly in the Procellarum KREEP Terrane [Hiesinger et al., 2004; Morota et al., 2011]. The absolute age determination relies on correlation between crater number density and age (chronology function), which is calibrated with the radiometric ages of the samples due to the Apollo and Luna missions [e.g., Neukum, 1983]. Since there are no returned samples showing $>$3.9 Ga and 3.0-1.0 Ga, however, the chronology curve has 0.5-1 Gyr of uncertainty in this range. To determine the shape of the chronology function is important not only for accurate age determination but also for understanding the temporal variation of the impact flux to the Earth-Moon system. For example, whether or not the impact flux has a spike around 3.9 Gyr ago, namely the lunar cataclysm hypothesis, is one of the main issues regarding the uncertainties of the impact flux [e.g., Gomes et al., 2005].

In-situ age measurements and/or sample-return mission(s) are needed to resolve this problem. We have been developing an in-situ dating method using K-Ar system for future planetary landing missions on the Moon or Mars [Cho et al., 2011, 2012]. The K-Ar dating method employs radiometric decay of 40K into 40Ar with half-life of 1.25 Gyr [Steiger & Jager, 1977]. This method requires much less technological developments than other dating methods, such as Ar-Ar, U-Pb, and Sm-Nd dating, because K is relatively abundant (~100 ppm-1 wt%) in the igneous rocks and Ar can be easily extracted (i.e., simply heat the sample). This leads to a simpler instrumental configuration. Our system measures the abundance of both K and Ar at the same laser irradiation spot on a sample using with two techniques (i.e., laser-induced breakdown spectroscopy (LIBS) and quadrupole mass spectrometer (QMS)). Potassium and argon are extracted from a sample simultaneously by the laser ablation, in which the sample is vaporized by a series of intense ($>$ 1GW/cm2) laser pulses.

Using our instrument, we measured three samples whose K concentrations and ages have been measured previously with flame photometry and a sector mass spectrometer: a hornblende (K2O=1.12 wt%, 1.75 Ga), a biotite (K2O=8.44 wt%, 1.79 Ga), and a plagioclase (K2O=1.42 wt%, 1.77 Ga) [Nagao, unpublished data]. We obtained the model ages of 2.1+/-0.3, 1.8+/-0.2, and 2.0+/-0.3 Ga, respectively. We measured K2O with a calibration curve constructed by measuring 24 geologic samples with known K2O concentration. The absolute amount of the extracted Ar is measured with the QMS. The sensitivity to Ar isotopes was calibrated by introducing the known amount of atmospheric Ar into the experimental system.

Since the three samples have similar ages and different K concentrations, we should be able to construct a "virtual" isochron by plotting the concentrations of K and $40Ar_{rad}$. The slope of the isochron simulated with our experimental data yields 1.34 Ga of age. The data with known values yields 1.79 Ga. Such underestimation probably results from both overestimation for K and underestimation for 40Ar in the biotite data, which have large weight for the regression. Nevertheless, a clear correlation between [K] and [$40Ar_{rad}$] is observed. Although further improvement in the accuracy of our measurements is necessary, the data obtained in this study demonstrate that our LIBS-QMS method can reproduce the trend essential for quantitative isochron-based age measurements.

キーワード: その場年代計測, K-Ar 年代, 惑星探査
Keywords: In-situ age measurement, K-Ar dating, Planetary explorations

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PCG32-13 会場:101B 時間:5 月 20 日 12:30-12:45

真空紫外LIBSによるその場K-Ar年代測定法
In-situ K-Ar dating using Vacuum Ultraviolet LIBS

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アポロ計画後の極軌道周回衛星観測によりアポロの着陸点は鉱物分布の観点から特殊な場所に集中していることが分かった. そのため年代推定においてアポロ岩石試料から得られる情報が月全体を代表しているとは言い難くなってきており, アポロ着陸点から遠方の場所での年代測定が急務となっている. しかし現時点では月試料を地球に持ち帰る他に年代を測定する手段がない. 近年ではクレータ数密度計測に基づいて形成年代が推定されているが, この手法で得られるのは各地域の相対的な年代関係のみであり, 絶対値較正には現在でもアポロのデータが使われている. アポロ 16 号で得られた岩石試料は, 39 億年前に多くの衝突メルトが形成された事を示している. この結果は, この時代に小天体の衝突が集中的に起きたとする Cataclysm 説の根拠であり, 最近の惑星形成理論であるニース・モデルの基盤となっている. 一方, その他のアポロ計画で得られた試料や隕石試料の測定結果からは, 39 億年前に集中的な小天体衝突があったことは必ずしも明白ではなく, 新たに年代測定が必要となっている.

我々はこの状況を打開するために, 月惑星着陸機にレーザ誘起絶縁破壊分光装置（Laser Induced Breakdown Spectroscopy, 以下 LIBS）を搭載し, 着陸点付近の形成年代を測定するための観測装置を検討している. LIBS は高出力のパルスレーザを岩石に照射し, 岩石表面の蒸発・プラズマ化に伴う発光を分光分析することで元素組成を測定する手法である. 2012 年 8 月に火星に着陸した Mars Curiosity に LIBS が搭載されており, カリウムを含む複数の主要元素輝線の検出に成功している. 一方, 地上実験においても岩石中に含まれるアルゴンが LIBS で測定されたことはない. これは LIBS による岩石の元素組成測定実験が主に空気の透過率が高い紫外-近赤外を中心に進められており, 真空紫外領域にあるアルゴン輝線 (106.7nm) の強度測定自体がなされていないためである. 本研究では LIBS に真空紫外分光装置を組み合わせる事で岩石に含まれるアルゴンの定量を目指し, 測定装置を開発している. 月面上の岩石に含まれる程度のアルゴンの検出は理論上可能であり, 実験検証が必要な段階である. 仮に月面試料に含まれる量と同程度のアルゴンが検出できない場合は, アルゴン雰囲気で形成されたアルゴンに富む合成試料を使って実験を行うことで検出限界を決定する. 月面のアルゴンを定量できることを確認した後に, 輝線強度に応じた定量精度の評価を行ない, 現在日本で検討段階の月着陸計画 SELENE シリーズや SLIM, あるいは海外の月惑星着陸探査機への搭載を見据え観測器の設計を行う. 月惑星着陸機用の「その場年代測定法」は既に複数の案が検討されているが, いずれも未だ実現には至っていない. これまでに検討されてきた手法では試料を着陸機内に収めるロボットアームが必要であるが, 本研究で開発する装置は光を使って遠方から測定でき, ロボットアームのない小型探査機への搭載が可能となる.

キーワード: LIBS, 年代測定, 惑星探査
Keywords: LIBS, Chronology, Planetary Exploration