

平原と山岳地帯での火星風力発電の見積もり Evaluations of wind electric energy at Martian Planitia and Mons

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惑星探査において、ローバーやランダーへの電力供給量はその運用能力を決定する重要な要因の1つである。現在、火星では太陽光が唯一の発電方法だと考えられている。しかし、火星表面に吹く強い風が太陽光発電に問題を引き起こすことがある。2010年の3月22日、火星探査車のMER-A(rover spirits)が着陸から2210火星日で活動を停止した。理由は電力の低下によるものである。太陽光パネルの上に風によって砂が運ばれ、発電量が低下したことが原因である。今学会では火星上での風力発電能力について発表する。いくつかの観測結果から、火星は風の強い惑星であるということが分かっている。Kaydash et al., 2006 は雲の動きから火星の高度30kmでは最大で80m/sの風が吹いていると見積もった。また、地表面の風速は着陸機VikingとPhoenixによって計測されている。また、火星上の風成地形からも表面の風速は見積もられている。Fenton et al., は砂の運搬能力から、Proctorクレーターの底の風速を20m/s以上だと見積もっており、Toyota et al., 2011 は傾斜面では更に強い風が吹いているとしている。

以上のことをふまえて我々は今回火星上の三カ所での風力発電量を見積もった。Elysium Planitia, Chryse Planitia, Arsia Monsの三カ所である。Arsia Mons その長い傾斜によって傾斜風が発生するため、火星上で最も風の強い場所の1つである。Elysium Planitia は InSight mission の着陸候補地の1つであり、Chryse Planitia は Viking Lander1 の着陸地である。これらの発電量は場所に強く依存する。同じ (sweep area が) 1平方メートルの風車を設置した場合、Chryse Planitia では一日に3.4[Watt hour]しか発電できない一方、Arsia Mons では137[Watt hour]の発電が見込まれる。この風力発電量を他の電力供給方法(太陽光発電と原子力電池)と比較し、火星上で風力発電は有効であると結論づけた。

キーワード: 火星, 風力発電, 惑星探査, 火星大気, 傾斜風

Keywords: Mars, Wind electric energy, Planetary exploration, Martian wind, Slope wind

初期火星大気中の主成分凝結対流の二次元数値実験

A 2D numerical simulation of atmospheric convection with condensation of major component under early Mars condition

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初期の火星においては大気主成分の凝結が広範にわたって生じ、CO₂ 氷雲の散乱温室効果が温暖な気候の実現に寄与したと考えられる (Forget et al., 2013). 散乱温室効果は雲の分布に強く依存し、雲の生成と分布を決める要因の一つは対流運動である。しかし大気主成分の凝結を伴う対流の構造についてはこれまでほとんど調べられていない。

Colaprete et al.(2003) は大気主成分が凝結する場合においても、臨界飽和比が 1.0 より大きく過冷却状態が維持されれば、凝結する気塊が浮力を得ることで対流が生じる可能性があるとして主張した。しかし Colaprete et al.(2003) が行ったのは 1 次元モデル計算であり、彼らの主張するシナリオが実現するかどうかは、空間 2 次元の数値流体モデルを用いて調べる必要がある。

我々は大気主成分凝結を考慮した 2 次元雲解像モデルの開発と、現在の火星の極夜での条件を与えた予備的な計算を行ってきた (例えば山下他, 2012 年連合大会)。本研究では初期火星条件の下での主成分凝結対流の数値計算を行い、臨界飽和比と凝結核数密度を変化させた際に流れ場と雲の分布がどのように変化するかを調べた。

支配方程式は山下他 (2012) 同様、大気主成分の凝結を考慮した 2 次元準圧縮方程式系である。雲粒の形成過程は拡散成長のみを考慮し、雲密度が閾値 (10^{-6}kg/m^3) 以下であれば過飽和が維持されると仮定する。この閾値は物理的には拡散成長する雲粒には臨界半径が存在することを考慮したものである。放射過程は陽に解かず、高度 0 km から 50 km までは水平一様な冷却、それより上空にはニュートン冷却を与える。水平一様な冷却率の大きさは -0.1 K/day (Kasting, 1991) とする。地表気圧は $2.0 \times 10^5\text{ Pa}$ 、地表温度は 273 K に固定する。初期の大気温度は高度 20 km 以下で乾燥断熱減率に従い、高度 20 km から 50 km まで飽和蒸気圧曲線に従い、高度 50 km より上で等温という分布を与える。臨界飽和比は 1.0, 1.35 (Glandorf et al., 2002)、凝結核数密度は 5.0×10^8 , 5.0×10^6 , $5.0 \times 10^4 / \text{kg}$ とし (Forget et al., 2013)、これらを組み合わせた 6 通りの数値実験を行なう。計算領域は水平 100 km、鉛直 80 km、格子間隔は水平 500 m、鉛直 400 m である。

臨界飽和比を 1.0 とした場合、凝結高度より上空にほぼ水平一様な雲層が準定常的に存在する状態が得られた。雲層内の鉛直流は凝結高度より下と比べると小さく、最大で 0.5 m/s である。これらの特徴は凝結核数密度によって変わらない。臨界飽和比が 1.35 の場合、雲の分布は凝結核数密度によって変化する。凝結核数密度を小さくすると、凝結が生じる期間と凝結が生じない期間が交互に出現するようになり、凝結期には厚い雲とともに 2-3 m/s の鉛直流が生じる。非凝結期には、雲密度が閾値未満である水平一様な雲層が存在し、そこでの鉛直流は最大で 0.5 m/s である。

以上より、大気主成分が凝結する系においては、臨界飽和比と凝結核数密度の値によって雲対流の時空間構造は大きく異なり、時間的に雲や流れ場があまり変動しない準定常解と、凝結期と非凝結期を交互に繰り返す準周期的な解が存在することが分かった。

キーワード: 大気主成分の凝結, CO₂ 氷雲, 雲解像モデル, 初期火星

Keywords: condensation of major atmospheric component, carbon dioxide ice cloud, cloud resolving model, early Mars

火星の冬極における CO₂ 大気凝結と傾圧不安定波の影響 CO₂ Snowfalls Affected by the Baroclinic Waves in the Winter Polar Atmosphere of Mars

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火星大気大循環モデル (MGCM) を用いて、火星冬極域における CO₂ 大気凝結について計算を行い、CO₂ 氷雲の生成と地表面への堆積が傾圧不安定波と密接に関わっていることを示した。

CO₂ 季節極冠は、大気中で凝結して生じた CO₂ 氷雲の地表面への堆積と地表面で直接凝結する CO₂ 大気により生成される。冬極における CO₂ 氷雲の存在は観測により示唆されており、また北極におけるその存在は局所的な気象現象の影響で経度方向に不均質となることが先行シミュレーション研究より示されている。とりわけ傾圧不安定波の存在は火星の北半球冬季において顕著な現象であり、本研究ではそれに代表される大気力学的な効果がいかんして北極域における CO₂ 氷雲や季節極冠の生成に影響しているかを示す。

今回我々は CO₂ 氷雲の凝結と輸送に関する簡単なスキームを MGCM に導入し、冬の北極域における CO₂ 降雪の再現実験を行った。数値計算結果では北緯 70 度以北・高度 40km 以下で CO₂ 氷雲の生成が見られ、その生成は傾圧不安定波により大気が寒冷化する位相に沿って見られた。高度 10km 以上で生成された CO₂ 氷雲はその大部分が地表面に達することなく、下部に存在する比較的温暖な大気層において蒸発する。また季節極冠となる地表面の CO₂ 氷のうち、その 9 割は大気中で生じた CO₂ 氷雲が地表面に堆積したものであり、地表面で直接大気が凝結して生じる季節極冠は全体のわずか 1 割である。そのため、CO₂ 季節極冠の生成率は高度 10km 以下の傾圧不安定波の位相に強く依存する。傾圧不安定波の規則性から、本研究の結果は CO₂ 氷雲の出現および地表面への堆積について予測の可能性を示唆するものであると言える。

キーワード: 火星, 大気力学, 大気大循環モデル, CO₂ 氷雲, 極冠

Keywords: Mars, atmospheric dynamics, general circulation model, CO₂ ice clouds, polar ice cap

火星気象オービター構想 Concept of Mars meteorological orbiter

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A Mars meteorological orbiter mission is under study. The primary objective of the orbiter will be exploration of meteorological processes with focusing on dust cycle. Water cycle and photochemistry will also be addressed.

In spite of tremendous efforts in Mars weather monitoring in previous Mars missions, dust and water cycle are far from fully understood. Though Mars Global Surveyor and Mars Climate Orbiter has provided a wealth of information on the seasonal cycle of large-scale dust storm and water vapor distributions, observations of individual meso- to synoptic-scale transport processes are limited due to spatially and temporary sparse sampling inherent in low-altitude polar orbits.

The Mars orbiter under study will address material transport over wide spatial and temporal scales with continuous, high-resolution global monitoring of dust, clouds, water vapor, minor gases, and temperature field from an elliptical, equatorial orbit. The apoapsis of the orbit will be located always near the local noon. The observation strategy resembles that of Earth's meteorological weather satellites, but the instruments are optimized to Mars weather monitoring. A polarimetric camera will visualize lofted dust grains and characterize the dust size distribution. A sub-millimeter sounder will obtain three-dimensional distributions of atmospheric temperature, water vapor, other minor gases and their isotopes. A thermal imager will monitor the global distributions of dust and atmospheric temperature, and also vertical profiles of dust with limb imaging. Radio occultation will obtain high-precision temperature profiles. The observations will complement other future Mars missions such as ESA's Trace Gas Orbiter, which focuses on high-sensitivity trace gas observations.

キーワード: 火星, 気象, 探査, オービター

Keywords: Mars, meteorology, exploration, orbiter

Prime Habitable Environment of Mars: Argyre Impact Basin Prime Habitable Environment of Mars: Argyre Impact Basin

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The geologic provinces of Mars, as identified through a synthesis of geologic, paleohydro-logic, topographic, geophysical, spectral, and elemental information [1], are windows into its evolution, such as the Hellas-Argyre province (middle to early Mars). The Argyre basin and surroundings, in particular, records long-term water enrichment and heat-energy, likely nutrient-enriched materials, and solar radiation, collectively making Argyre a prime habitable environment for the exploration of possible life [2-4]. The giant impact event tapped into primordial mantle and granite-enriched crustal materials, including rocks enriched in elements which are critical to life (including P,O,N,C,H,S,Ca,Fe; see [Shigenori Maruyama, this conference]), creating a catchment for water and rock materials since its formation about 4.0 Ga [1-3].

A lake was formed directly subsequent to the event, feeding the far-reaching Uzboi Vallis system; other lakes filled the impact-derived local basins as well. The lakes soon froze, and the once lacustrine environment transitioned into glacial and periglacial environments. Through time, liquid water/water-ice waned, though not totally being depleted, as there was subsequent Tharsis superplume-driven, transient hydrological cycling at global scale [3] (including enhanced activities in the basin region).

Long-term water enrichment in and surrounding the Argyre basin includes geologically-recent and possibly present-day periglacial and glacial activity [5,6]. The major topographic variations between the deep catchment basin and nearby Tharsis-superplume plateau may have resulted in enhanced precipitation through time resulting from both endogenic activity (e.g., Tharsis) and exogenic activity (e.g., obliquity).

In addition, the impact produced a complex system of tectonic structures, many of which are thousands of kilometers in length and reach great depths (likely the Moho). Such basement structures served as conduits for the migration of volatiles and heat energy into the basin region from as far away as Tharsis [1-3].

Yet another important habitable-environmental condition is the long-term heat generated by the impact. There even appears to be geologically recent venting along the basin floor as well as reactivation of the impact-generated basement structures. Such an interplay among long-term water enrichment and heat-energy, likely nutrient-enriched materials, and solar radiation collectively point to Argyre basin as a prime habitable environment for exploration of possible life.

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MELOS1 火星着陸機のサイエンスと着陸候補地点 Science and landing-site candidates of the MELOS 1 EDL demonstrator

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MELOS (Mars Exploration with a Lander-Orbiter Synergy) is a Japanese Mars-exploration mission proposed by the Japan Aerospace Exploration Agency. Through a few years of discussions of its both scientific and engineering aspects, the outline of the mission becomes clearer. Most importantly, MELOS now stands for a concept of a series of missions; the MELOS 1 will focus on an accurate orbital insertion with an entry-decent-landing (EDL) demonstrator for future Mars missions, which will be followed by a full-scaled MELOS 2 or later missions.

MELOS1 emphasizes its engineering aspects, however, the EDL and the orbiter carries a fair amount of science payload to perform geologic and atmospheric investigations to expand our knowledge of the red planet. In this talk, we will report an update on the EDL of the MELOS 1 mission, especially about its size/orbital parameters as well as its scientific goal and potential landing sites.

キーワード: 火星, 着陸機, 生命, ダスト, 水

Keywords: Mars, Lander, life, dust, water

Magnetic hysteresis measurement of magnetite under high pressure: Implication for source of the Martian magnetic anomaly

Magnetic hysteresis measurement of magnetite under high pressure: Implication for source of the Martian magnetic anomaly

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Mars Global Surveyor observed the magnetic field of Mars, and revealed that there are many strong magnetic anomalies [1]. The strong magnetic anomalies suggest an active core dynamo of early Mars (about 4 billion years ago), and some mechanism of crustal formation in the dynamo field. Since magnetic properties of crustal rocks depend critically upon the mineralogical form of magnetic particles, the strong magnetic anomalies can give crucial information about the chemical composition and oxidation state prevailing in the early Martian crust. However, source of the magnetic anomalies have been poorly understood yet because of the lack of basic information concerning magnetic properties of deep crustal rocks. Here, we report laboratory magnetic experiments to interpret the source of the Martian magnetic anomaly.

According to previous analyses of the Martian anomalies [2,3,4], sources of the anomalies have to satisfy the following requirement: (1) the crustal rock on average is more intensely magnetized than terrestrial continental crust, (2) there may be a continuous non-magnetized layer at the surface (about 10 km), and (3) the magnetic layer is thick (about 30 - 40 km). Moreover, it is well known that remanent magnetization of the magnetic mineral gradually decays in a null field and at a temperature lower than the Curie point [5]. Thus, magnetic minerals of the Martian crust, probably magnetite [6], should have retained their magnetizations under high pressure and temperature for about 4 billion years.

In this study, we have conducted in-situ magnetic hysteresis measurement of magnetite under high pressure up to 1 GPa by using the high-pressure cell specially designed for a Magnetic Property Measuring System (MPMS). Based on the experimental results, systematic rock magnetic properties of multi-domain (MD), pseudo-single-domain (PSD), and single-domain (SD) magnetite were first obtained for high pressure up to 1 GPa. The results show that magnetite exhibits various pressure dependences with respect to magnetic domain states. Both MD and PSD magnetite particles, the coercivity monotonously increases with pressure at a rate of +90 %/GPa. On the other hand, the coercivity of SD magnetite is almost constant in the pressure range by 1GPa.

Taking into account new results of pressure dependences of hysteresis parameters, relaxation time of remanent magnetization in the Martian crust was calculated as a function of depth and age. As a result, remanent magnetization carried by MD and PSD magnetite would have been demagnetized within 4 billion years, except very shallow crustal part (shallower than 5 km). On the other hand, the SD magnetite could stably retain its magnetization in the entire crust. Therefore it is concluded that source of the Martian magnetic anomaly is probably elongated SD magnetite with submicron size, suggesting that chemical composition and oxygen state in the Martian crust was suited for bearing fine grains of magnetite about 4 billion years ago.

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キーワード: Magnetite, High-Pressure, Magnetic Hysteresis, Martian Magnetic Anomaly

Keywords: Magnetite, High-Pressure, Magnetic Hysteresis, Martian Magnetic Anomaly

火星表層水の水素同位体組成

A moderate hydrogen isotope composition of the surficial water reservoir on Mars

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Martian surface morphology implies that Mars was once warm enough to maintain persistent liquid water on its surface and that water played a significant role in the formation of weathered/altered terrains. This study characterizes Martian surficial volatile reservoirs based on in situ ion microprobe analyses of volatile abundances and H-isotopes of glassy phases (groundmass glass [GG] and impact melt [IM]) in Martian basalts (shergottites). Although these meteorites are of igneous origin, some glassy phases underwent impact-induced modification that trapped surficial and atmospheric volatile components. Analyses of these glassy phases demonstrate that surficial volatile reservoirs have distinct D/H ratios from their magmatic volatiles.

Hydrogen isotope compositions and the abundances of volatile elements (H₂O, CO₂, S, Cl, F) of IMs and GGs have been measured using an ion microprobe (Cameca ims-6f) at DTM-CIW. This study employs three olivine-phyric shergottites: Y-980459 (Y98), LAR 06319 (LAR06), and Lithology-A of EETA79001 (EETA79). These meteorites are petrographically similar, but are geochemically distinct in terms of their radiogenic isotopes and incompatible trace elements. The composition of Y98 closely approximates a Martian primary melt that was directly derived from a geochemically depleted mantle reservoir. In contrast, LAR06 represents a melt that has assimilated a geochemically enriched Martian crust. EETA79 shows an intermediate geochemical signature, which is interpreted to reflect mixing of the depleted and enriched sources represented by Y98 and LAR06, respectively.

IMs in LAR06 contain lower H₂O (~150ppm), CO₂ (~20ppm) and S (100-400ppm) but higher F (10-30ppm) and Cl (40-80ppm) than IMs in EETA79 (~300ppm H₂O, ~300ppm CO₂, 3200ppm S, <3ppm F, ~30ppm Cl). The major element compositions of IMs are probably derived by partial melting of primary plagioclase and pyroxene. Likewise, the halogen abundances and high-P₂O₅ contents in the LAR 06 IMs could possibly reflect the incorporation of primary phosphates. Y98 GGs contain low H₂O (20-50 ppm) contents relative to F (15-30 ppm) and Cl (30-50 ppm). The high halogen/H₂O ratios in Y98 GGs, compared to those of Y98 primary magma [1], indicates degassing of magmatic water during eruption.

In our previous study [1] based on olivine-hosted melt inclusions we showed that the primary magma of Y98 had a chondritic low-dD (delta-D) value of 275 permil, whereas that of LAR06 had a very high-dD value of 5079 permil. In contrast with such extreme dD differences, matrix phases in Y98 and LAR06 both have moderate dD values. GGs in Y98 exhibit a slightly greater dD variation of 200-1600 permil, but still much less extreme than the range exhibited by the melt inclusions. The dD values of the Y98 GGs rise with increasing water contents, implying mixing of two components: near-surface moderate-dD and magmatic low-dD components. On the other hand, IMs in LAR06 exhibit lower dD values of ~1000-3000 permil than the primary LAR06 melt (5079 permil). IMs in EETA79 also have a moderate dD value of ~1600 permil.

This study shows that the matrix phases (GG and IM) in all three shergottites have a relatively limited range of dD values regardless of the distinct dD of their magmatic sources. A dD-1/H₂O mixing diagram shows a convergence among the matrix dD values, which could be attributable to the impact-induced addition of a common near-surface water with a moderate dD value (~1500-2000 permil). The origin of this surficial water reservoir remains unresolved: (1) it may be derived from the Martian atmosphere, but its moderate dD values are distinctly lower than the widely-accepted atmospheric dD value of ~4000-5000 permil, and/or (2) it could originate from the addition of a weathered soil/dust component enriched in volatile elements.

[1] Usui, T., et al. (2012) EPSL, 357-358, 119-129.

キーワード: 火星, 表層水, 水素同位体

Keywords: Mars, surficial water, hydrogen isotope

火星内部構造探査: InSight の紹介

An Introduction to the Exploration for the interior of Mars: InSight

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The InSight mission (Interior Exploration Using Seismic Investigations, Geodesy, and Heat Transport) will illuminate the fundamental processes of terrestrial-planet formation and evolution by performing the first comprehensive surface-based geophysical investigation of Mars. It will provide key information on the composition and structure of an Earth-like planet that has gone through most of the evolutionary stages of the Earth up to, but not including, plate tectonics. Thus, the traces of this history are still contained in the basic parameters of the planet: the size, state and composition of the core, the composition and layering of the mantle, the thickness and layering of the crust, and the thermal flux from the interior.

InSight will delineate these parameters with a focused set of three investigations centered on seismology and supported by precision-tracking and heat-flow measurements. Rather than relying on a geophysical network to provide this information, InSight will utilize state-of-the-art analysis techniques to derive interior information from a single station on the surface carrying two scientific instruments: an ultra-sensitive, very-broad-band seismometer (SEIS); and a Heat Flow and Physical Properties Probe (HP³) that consists of a self-penetrating mole trailing an instrumented tether. An X-band transponder (part of the communication system) to enable two-way precision Doppler tracking of the planet's rotation comprises the Rotation and Interior Structure Experiment (RISE). Monitoring surface environment is also performed by a high precision barometer, thermometer and anemometer (PTW), and magnetometer (MAG).

The launch and landing of InSight will be in Mar and Sept 2016 respectively, and the science operation period is one Mars year. The landing and deployment systems are inherited from Phoenix. A robotic arm and cameras are used to deploy the geophysical instruments to the surface. The system and instruments of InSight, and hence science objectives, are very similar to those investigated by the MELOS (Mars Exploration with Lander-Orbiter Synergy) EDL team. Thus InSight is of great interest to Japanese scientists and has many points from which they can learn. Conversely, the participation of Japanese scientists brings considerable strength to InSight as well, and we are pleased with their contributions.

The knowledge provided by the InSight mission will substantially advance understanding of the formation and evolution of terrestrial planets. This is a chance to open the door into the interior of Mars for the first time. We welcome your participation!

キーワード: 火星, 内部構造, 探査, 地震波, 地球物理学の観測, 気象観測

Keywords: Mars, internal structure, exploration, seismic wave, geophysical observation, meteorological observation

Pre-Noachianにおける水の散逸：火星隕石中の水素同位体による制約 Significant Water Loss during pre-Noachian era: Constraints from Hydrogen Isotopes in Martian Meteorites

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Martian surface morphology implies that Mars was once warm enough to maintain liquid water on its surface (Jakosky and Philips, 2001). Although the high D/H ratio (~ 4500 per mil) of the current Martian atmosphere and hydrosphere (Owen et al., 1981; Jakosky and Philips, 2001) suggests that significant water should have been lost from the surface by the atmospheric escape during the Martian history, the timing and amount of the water loss have been poorly constrained. Whereas previous studies have focused on the water loss after the cessation of Martian dynamo (Lammer et al., 2003), studies for the pre-Noachian period (4.5 - 4.1 Ga) and the Noachian period (4.1 - 3.7 Ga) are limited.

Recent technical developments of ion-microprobe analysis have provided more accurate estimation of hydrogen isotope compositions (D/H) in Martian meteorites which inform the evolution of Martian water reservoirs (Usui et al., 2012; Bockor et al., 2003; Greenwood et al., 2008). Based on the D/H data from the meteorites, this study determines the amount of water loss during each period.

The water losses are estimated with a one-box model. The model is similar to Lammer et al. (2003). We assume that surficial water is lost in two stages: Stage-1 (4.5 - 4.1 Ga) and Stage-2 (4.1 Ga - present). Stage-1 corresponds to pre-Noachian era. The boundary (4.1 Ga) is derived from the crystallization age of ALH 84001, the only Martian meteorite formed in Noachian (Lapen et al., 2010). The D/H ratio at 4.1 Ga is 1200-3000 per mil. The values are derived from analyses of magmatic phosphate and secondary carbonate minerals in ALH 84001 (Bockor et al., 2008; Greenwood et al., 2008). The D/H ratio at 4.5 Ga is < 275 per mil which is the value of melt inclusion in Yamato 980459 (Usui et al., 2012) and thought to represent the primitive D/H ratio of Mars. We use present water amount as an input parameter. The water losses in both stages are obtained as outputs.

Our results show that the water loss was more significant in Stage-1 (4.5 - 4.1 Ga) than in Stage-2 (4.1 Ga - present), indicating significant water loss during pre-Noachian era. This result is independent from the estimation of present water amount. Present water reservoirs exist mainly as polar layered deposits (PLD), which corresponds to $2-3 \times 10^6 \text{ km}^3$ (Zuber et al., 1998; Plaut et al., 2007). The amount is 20-30 m of global equivalent layer (GEL). Using this value and assuming an efficient fractionation, minimum values of water losses are obtained as 35 - 85 m and 5.7-41 m (GEL) in Stage-1 and Stage-2, respectively. The sum of these values yields 82-120 m GEL for the total water reservoir at 4.5 Ga.

Our minimum estimate of the initial water reservoir are consistent with the amount of ocean (~150 m) provided by Vastitas Borealis Formation (VBF) (Carr and Head, 2003). Also, minimum estimates of the water losses in Stage-1 and Stage-2 are close to the values obtained by simulations of oxygen escape (Lammer et al., 2003; Terada et al., 2009). The significant water loss during pre-Noachian (> 4.1 Ga) might have been caused by the intense atmospheric escape due to the solar wind without magnetic protection at the first ~150 Myr of the Mars history (Terada et al., 2009) before the time when Mars obtained ancient magnetic field.

キーワード: 火星, 隕石, 水素同位体, 大気散逸

Keywords: Mars, meteorite, hydrogen isotope, atmospheric escape

火星大気散逸観測ミッションの検討報告 Examination of Orbiters for Martian Atmospheric Escape Study

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火星の大気の変遷には、太陽風との相互作用が大きく影響したと考えられているが、今現在の火星においてさえ、大気と太陽風との相互作用の物理プロセスは明らかになっていない。

地球と異なり、現在の火星は惑星固有の磁場を持たない。その結果、太陽風は低い高度にまで達し、火星の大気と直接相互作用して、火星大気の一部は散逸される。この過程は、長い間には火星大気の組成を変化させるまでの作用を及ぼし、火星大気や、ひいては地上・地下の二酸化炭素（ドライアイス）や水・氷の変遷に大きく影響した可能性があると考えられている。大気散逸の様子は、太陽活動や太陽との距離によって影響を受けるため、大気の長期的な変遷を考えるためには、様々な太陽の状態について相互作用の働きを知らなければならない。

我々は、2011年12月にJAXA宇宙科学研究所理学委員会において火星大気散逸探査検討ワーキンググループを発足させた。このワーキンググループは、大気散逸に焦点を当て、2つのオービターによって散逸の全体像とプロセスを同時に観測することを検討している。1つのオービター（大気散逸その場観測衛星）によって、大気散逸が起きているその場のプラズマや中性粒子の観測を観測を行い、もう1つのオービター（リモート観測衛星）によって、散逸する大気等から発せられる光をリモートで撮像し、また同時に太陽風をモニターするというものである。大気散逸の物理プロセス、グローバルな全体像、物理プロセスを決める太陽風のモニターを同時に行うことは、複数衛星によって初めて可能となる、真に大気散逸の全容解明に迫る観測である。

現在我々は、2024年頃の太陽活動極大期における火星観測を行う大気散逸観測オービターの実現に向けて、サイエンス・観測機器・衛星の検討を行っている。まず海外の類似ミッションに対する優位性や差別化を意識しながら、サイエンス目標の定量的・具体的な策定を行う。更に、現在の機器技術でサイエンス目標を達成できるのか、どのような技術開発が必要なのか、今後の開発計画を明らかにする。更に、この計画を実現させるための衛星構成や、軌道計画を検討する。

本講演では、これらの課題について検討を行った途中経過を報告する。

キーワード: 火星, 大気, 太陽風

Keywords: Mars, atmosphere, solar wind

すばる望遠鏡によって得られた火星 CO₂ 同位体分布 Global mapping of the CO₂ isotopologues in the Martian atmosphere as observed Subaru/IRCS

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We investigated Martian CO₂ isotopic ratios at 2-4 micron spectra observed by Subaru IRCS.

The determination of the isotopic ratios on Mars is important to study atmospheric evolution. The relative abundance of isotopes of CO₂ provides insight into the loss of Mars primordial atmosphere. In addition, the distributions and variations of C and O isotopes can constrain the information about the magnitude and distribution of sources and sinks of CO₂, i.e. the global coupling between surface, aerosols, and atmosphere. Photochemical reaction, condensation into the polar caps and aerosols, soil and subsurface reservoir respiration impart C and O isotope signals to the atmosphere that can be used as a tracer at various temporal and spatial scales.

High-resolution global imaging spectroscopy of Martian CO₂ isotopologues has been achieved at 2-4 micron (2970-3050 cm⁻¹) by IRCS with Subaru telescope on 30 November 2011 (Ls=37), 4-5 January 2012(Ls=52), and 12 April 2012 (Ls=96). Owing to its wide wavelength coverage, our measurements obtained a comprehensive dataset of CO₂ isotopes (626, 627, 628, and 636) & water vapor isotopes (H₂O and HDO) simultaneously, providing a global perspective on their near-surface distributions.

Spectra were collected in the northern hemisphere at a spectral resolution of R=20,000. The diameter in these periods of Mars was more or less 9 arcsec. The seeing was 0.5-0.8 arcsec (pixel scale: 0.06 arcsec). We used two slit positions. The slit along the N-S direction on Mars covered the region between the northern polar cap and the equator, in order to investigate the sublimation of the polar cap and condensation into the CO₂ ice clouds at mid-latitude. The W-E direction of the slit position was also selected in order to clarify the local-time dependence surrounding of sub-solar area. The mud volcanic regions, Utopia/Isidid Nilli Forssae, Sytris Major, were also covered by these observing runs.

Terrestrial absorptions were reduced using standard-star calibrations in order to retrieve the Martian isotope lines. After that, we could successfully obtained clear CO₂ isotopes (626, 627, 628) absorptions in the range of 3330-3380 cm⁻¹ for 626, 2620-2640 cm⁻¹ for 627, and 2630-2660 cm⁻¹ for 628, respectively. The 3400 cm⁻¹ range shows lines of 636. Finally, the chosen spectral range involves plenty good enough lines of the Martian CO₂ isotopes.

In this paper, we will present these isotopologues, their distributions, and seasonal variations. Their S/N will be quantitatively discussed.

キーワード: 同位体, 二酸化炭素, 火星

Keywords: Isotope, carbon dioxide, Mars

火星大気大循環モデルで表現される火星中層大気子午面循環 Meridional circulation of Martian middle atmosphere represented by a Mars general circulation model

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Observations by Mars Climate Sounder (MCS) onboard Mars Reconnaissance Orbiter spacecraft provided the meridional temperature structure of Martian middle atmosphere up to about 90 km altitude. These observations enable us to compare the model produced middle atmosphere with observational ones and examine the nature of Martian middle atmosphere. In this study, structure of Martian middle atmosphere is investigated by use of a Mars General Circulation Model (GCM).

A planetary atmosphere GCM, dcpam, is used in this study. Dynamical core of dcpam solves the primitive equation system by use of spectral transform method with the finite difference method in vertical direction. The included physical processes are the radiative process, the turbulent mixing process, and the surface processes. Further, a condensation scheme of CO₂ is included. By the use of a "Mars mode" of this model, several experiments have been performed. In the experiments, the dust distribution in the atmosphere is prescribed. In the vertical direction, the Conrath-type distribution is assumed. In the horizontal direction, the optical depth is prescribed in two ways. Those distributions will be described below. The resolutions used for this study is T21L32, which is equivalent to about 5.6 degrees longitude-latitude grid and has 32 vertical levels. Under these conditions, the model is integrated for 5 Mars years from an initial condition of isothermal atmosphere at rest. The result during the last Martian year is analyzed.

The model is evaluated by comparing the temperature structure simulated by the model with that observed by the MCS. In the simulation, the dust optical depth is prescribed based on the "climatology", which has been created by averaging dust optical depth observed by Thermal Emission Spectrometer onboard Mars Global Surveyor spacecraft. It is found that the gross features of temperature structure observed by MCS are represented by the model, such as the strong latitudinal temperature gradient at southern middle latitude, and the latitude of highest near surface temperature. However, some differences can also be observed. One of that is the strength of temperature increase in southern middle and high latitude at about 1 Pa pressure level (~60 km). This temperature increase is caused by adiabatic heating in a descending branch of meridional circulation. The difference of this temperature increase between the model and observation implies the failure in representing strength of meridional circulation in the model. One of plausible explanations for the failure would be the lack of representation of the effects of subgrid scale atmospheric waves, such as gravity waves. Similar biases were observed in Earth's atmosphere models without (non-orographic) gravity wave drag parameterization.

In order to examine the driving mechanisms of meridional circulation in the middle atmosphere, three experiments are performed: (I) an experiment with Rayleigh friction in the middle atmosphere, (II) an experiment with diurnally mean solar insolation, and (III) an experiment with zonally averaged surface topography, albedo, and thermal inertia. Those three experiments are intended to examine the effects of subgrid scale atmospheric waves, such as gravity wave, thermal tides, and orographically related waves, such as topographic Rossby waves, respectively. The Rayleigh friction coefficient in the experiment (I) is chosen to reproduce the middle atmospheric polar temperature increase observed by MCS roughly. The difference in peak values of mass stream function at 1 Pa pressure level between each experiment and control experiment at northern winter are 0.2e8, 0.15e8, and 0.15e8 kg/s, respectively. This result implies that the subgrid scale atmospheric waves, the thermal tides, and the orographically related waves contribute to middle atmospheric meridional circulation by the similar degree.

キーワード: 惑星大気, 大気大循環モデル, 火星, 中層大気

Keywords: planetary atmosphere, general circulation model, Mars, middle atmosphere

火星の Amazonis Planitia における最近の火山活動の検討 Recent magmatism in Amazonis Planitia, Mars

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On Mars, several young volcanic fields have been discovered such as at Tharsis region, Acidalia Planitia, Utopia Planitia, Isidis Planitia, Elysium Planitia, and Amazonis Planitia (e.g. Fagents and Thordarson, 2007, Jaeger et al., 2010). Some of these volcanic field seem to consist of flood lava plain and volcanic cones (e.g. Jaeger et al., 2007, Hamilton et al., 2010). It is interesting whether the recent magmatism is different from those of large edifice-build-up type. For example, in Central Elysium Planitia, there exist vast smooth plain. Since a lot of cones are found on this plain, which are identified as rootless cones, the surface is interpreted to be covered by young fluidic lava, which emanated from Cerberus Fossae (e.g. Jaeger et al., 2007, Noguchi and Kurita, 2012). But there exist quite few investigation focusing on the style of recent magmatism except Central Elysium Planitia. In this report we describe the style and extent of recent magmatism at Amazonis Planitia.

Amazonis Planitia is also famous for its young smooth plain, although only a few paper stated its origin. Fuller and Head, 2002 stated Southern Amazonis Planitia (SAP) is covered with lava flow from Tharsis region in Early Amazonian, while Northern Amazonis Planitia (NAP) is occupied with lava from Cerberus Fossae via Marte Valles in Early Amazonian to Mid Amazonian. On the other hand, Tanaka et al., 2005 and Harmon et al., 2012 stated that SAP lava should have a local source. While its young origin has been well documented by crater chronology, identification of the volcanic origin seems insufficient such as the point whether the smooth plain is fluidic lava flow or not. Volcanic cones are important morphology for the inspection of flood lava magmatism on Mars. Types, distributions, and shapes of volcanic cones tell us its volcanic origin rather than mud flows, and the style of the magmatism. In this presentation, we focus on the volcanic cone morphologies in Amazonis Planitia. We surveyed its spatial distribution and the size by using CTX and HiRISE images.

キーワード: 火星, 火山, 火砕丘, 溶岩平原, ルートレスコーン

Keywords: Mars, volcano, volcanic cone, lava plain, rootless cone

惑星の大きさがプレートテクトニクス・熱史に与える影響：火星への応用 Large Effect of Small Planet on Plate Tectonics and Thermal Evolution: Application to Mars

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The likelihood of plate tectonics on other planets has been investigated especially in the last two decades (e.g., Solomatov and Moresi, 1997). In terms of a larger planet than the Earth, a super-Earth is an instance. Geodynamicists have analyzed the probability that plate tectonics operates on its surface, and some results claim that the plate tectonics is conceivable (Valencia et al., 2007). As regards a smaller planet than the Earth, Mars is a representative example. Although several observations of the Martian surface indicate the existence of plate tectonics for the first ~500 Myr, calculated thermal history with plate tectonics (Nimmo and Stevenson, 2000) seems inconsistent with other observations (e.g., Baratoux et al., 2011) and, as a result, the early Martian plate tectonics was concluded to be unlikely (Breuer and Spohn, 2003). To those planets, this study applies the thermal evolution model of the Earth, which has been investigated much more than the other planets, and especially follows a recently proceeded theory about thermal evolution with plate tectonics on Earth (Korenaga, 2006). In addition to the application, focusing on the effect of gravity, in particular small gravity of Mars, this study provides its thermal history, which shows the early Martian plate tectonics conceivable.

Calculation of thermal history mainly follows the theory developed by Korenaga (2006), which includes the effect of plate thickness generated at the mid-ocean ridge by decompression melting. This thermal history model is consistent with geochemical or petrological data of the Earth (Korenaga, 2008; Herzberg et al., 2010). I applied the theory to different-size planets on the assumption that plate tectonics is operating on their surface. I focus on the influence of thickening plate due to the small gravity on a small planet, like Mars, since the effect helps keep the heat of small planet.

First, in order to clarify the effect of plate thickness variation on the Martian early thermal history, I calculate the initial time rate of change of temperature, $dT(t=4.5\text{Ga})/dt$, with variation of planet size, which shows that a planet smaller than the critical size, ~ 1.1 Earth size, such as the Earth and Mars, first increases the temperature, though a larger planet decreases the temperature as we conventionally expected. Secondly, I calculate the early thermal evolution of Mars with plate tectonics to 4.0 Ga and then employ the stagnant-lid convection (Schubert and Spohn, 1990) from 4.0 Ga to the present, which shows two important results. The first one is that the application of the Earth's thermal history with plate tectonics to Mars enables us to reproduce a conceivable Martian thermal history. Second, if the plate tectonics ceased at 4.0 Ga, the cessation occurred in a hotter condition than the initial one, though the mantle must have convected more vigorously than ever.

Whereas those results depends on some uncertain parameters, such as the initial temperature and the geometry of subducting slab, those uncertainties do not change the essence, that is, Mars with plate tectonics tends to keep the heat in. It means that, if there was plate tectonics in the early stage of Mars, the drastic temperature drop shown in a conventional theory (Nimmo and Stevenson, 2000) is unlikely, which results in a realistic temperature evolution after the cessation of plate tectonics. In addition, plate tectonics cessation with the hot mantle at 4.0 Ga means that other factors than temperature are indispensable to retain plate tectonics, such as liquid water on the surface. As future works, we should consider other observational data, such as Martian morphology, to constrain this thermal model of Mars.

キーワード: 火星, プレートテクトニクス, 熱史

Keywords: Mars, Plate tectonics, Thermal Evolution

火星における Recurring Slope Lineae の地形学的特徴と成因 On the formational processes of Recurring Slope Lineae on Mars

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近年急速に進む火星探査によって、火星が完全に乾燥しきった天体ではなく、現在においてもごく短い時間であれば液体の水が流出している可能性があること、示唆されるようになった。その一例として、マーズリコネサンスオービター搭載の HiRISE カメラの高解像度画像の解析結果から明らかになった、Recurring Slope Lineae (RSL) と呼ばれる一連の微地形がある。

RSL は、火星の南半球の中緯度にある Newton Crater などの斜面に広範囲にわたって認められ、液体が流れたような跡を形成することが知られている (McEwen et al. 2011)。RSL は春から秋の温暖な季節に現れ、冬には消えるという挙動を年毎に繰り返すと考えられている。火星にはアウトフローチャネルなどの水成地形があることが知られているが、これらは 30 億年以上前に形成されたものである。一方、現在でも活動しているとみられる RSL は液体の水が現存することを示唆する極めて重要な地形であるといえる。もし RSL が液体の水が流れて形成されたものであったならば、火星が液体の水を保持していることを意味し、現在も活動的であることを示す。

寒冷な火星表層に水が液体のまま残されている要因として、塩による凝固点降下が考えられる。しかし、RSL の成因や水源、季節性の理由など、詳しいことはわかっていない。

そこで本研究では、緯度 - 20 度から - 50 度を中心に、全経度にわたり約 100 個の HiRISE の衛星画像について、RSL およびその可能性のある地形を徹底的に探し出し、一部においては新たに HiRISE ステレオ画像から構築した高解像度高度データ (DEM) を対比することで、RSL の勾配や分布の傾向、流れの特徴などの性質について、定量的な調査を行った。その結果、約 30 度の勾配のものが多く、緯度 - 40 度付近に多く分布している (経度には目立った傾向はなくばらついている)。1 つ 1 つの流れの幅は 1 - 5m (太く見えるものは合流しているから)。流長は長いものでも約 500 m で、それ以上は延伸しない。という傾向がみられることがあきらかになった。これらは RSL が液体の水で形成されたとする指摘と調和的である。

キーワード: 火星, 地質, 水, 衛星画像, 生命探査

Keywords: Mars, Geology, Water, Orbiter images, Life exploration

火星のアシダリア平原におけるピットドコーンの超高解像度地形解析 HiRISE-based topographic analysis of pitted cones in the Acidalia Planitia on Mars

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The presence or absence of liquid water within the martian sub-surface for the past ~ 2.0 Gy is still under debate. Low-relief circular mounds with summit pits, called as pitted cones, are commonly identified on the early Amazonian-aged surface in the martian northern lowlands. Although pitted cones are previously interpreted as rootless cones, cinder cones, pingoes, or mud volcanoes [Tanaka et al., 2005], high-resolution images obtained by the recent observations indicate that these pitted cones are likely sedimentary features formed by the fluid flow [Oehler and Allen, 2010]. However, physical characteristics of the materials forming the pitted cones are not critically estimated.

Using the HiRISE stereo pairs, we develop high-resolution (up to 1 m/pix) DEMs (Digital Elevation Models), which enables us to accurately measure the relative heights and basal diameters of the pitted cones. We study 140 pitted cones in the southern Acidalia Planitia, known as the early Amazonian terrain. As a result, we find that these pitted cones have the relative heights of 7 to 64 m (median 22 m) and the basal diameters from 222 to 1377 m (median 579 m).

The high-resolution DEMs are used to calculate the yield strengths and the viscosities of the materials forming the pitted cones. Assuming that the materials have Bingham rheology [Hulme, 1974; Major and Pierson, 1992], we can obtain 10^2 - 10^4 Pa for the yield strengths and the range of 10^1 to 10^6 Pa s for the viscosities for those materials forming the pitted cones. This result strongly indicates that pitted cones are formed by the mud-volcanic activities. Applying a simple buoyancy model to these potential mud volcanoes [Murton and Biggs, 2003], we estimate that the depths to mud sources range from 27-247 m with a median value of 86 m (std. dev. 40 m). In summary, we conclude that (i) liquid water had been preserved in ~ 40 m-thick reservoir layers formed about 86 m under the surface in southern Acidalia Planitia and (ii) after that, the fluidized mud erupted from the mud source layers formed mud volcanoes on the surface of Mars.

キーワード: 火星, アシダリア平原, ピットドコーン, 数値標高モデル, 泥火山

Keywords: Mars, Acidalia Planitia, pitted cone, digital elevation model, mud volcano