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論　文　内　容　要　旨

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学位論文の題　　　目	Spectral and mineralogical analyses of laser-irradiated and naturally-heated carbonaceous chondrites to elucidate the formation and evolution process of C-type asteroids (C 型小惑星の形成進化過程の解明に向けたレーザ照射・加熱脱水炭素質隕石の分光学および物質科学的研究)		

論　文　目　次

Chapter 1. Space weathering simulation with low-energy laser irradiation of Murchison CM chondrite for reproducing micrometeoroid bombardments on C-type asteroids........... 6

Abstract 6

1. Introduction.. 7

2. Methods 8

2.1. Experimental methods.. 8

2.2. Reflectance spectra measurements... 8

2.3. Field emission scanning electron microscope (FE-SEM) observation 9

2.4. Raman spectra measurements 9

3. Results... 10

3.1. UV-Vis-IR Reflectance Spectra 10

3.2. FE-SEM observation... 11

3.3. Raman analysis 11

4. Discussion.. 12

4.1. Mineralogical change due to laser heating... 12

4.2. Spectral and mineralogical change caused by laser heating 13

4.2.1. Albedo change.. 13

4.2.2. Spectral slope decreasing 14

4.2.3. 0.7- and 3-μm bands weakening 14

4.3. Comparison between laser-irradiation and ion-irradiation experiments........... 15

5. Conclusions.. 16

Chapter 2. Spectral and mineralogical studies using naturally-heated carbonaceous chondrites 26
Abstract 26
1. Introduction 27
2. Samples and analytical procedures 28
2.1. Samples 28
2.2. Analytical methods 29
2.2.1. Spectral measurements 29
2.2.2. Field emission scanning electron microscope (FE-SEM) and transmission electron microscope (TEM) analysis 30
3. Results 30
3.1. The in-situ heating effects for the 3-μm absorption band 30
3.2. Reflectance spectra of hydrated and dehydrated carbonaceous chondrites 31
3.3. Mineralogy of hydrated and dehydrated carbonaceous chondrites 33
4. Discussion 34
4.1. Comparison between IR spectra measured at room temperature and those of in-situ heating 34
4.2. Mineralogical changes of carbonaceous chondrites due to heating process 35
4.2.1. Albedo change 37
4.2.2. 0.7- and 3-μm bands weakening 38
4.2.3. CF and RB changes 38
4.3. Comparison between long-duration heating and short-duration heating 39
5. Application to asteroidal spectra 42
5.1. Comparison between space weathering and heating process on C-type asteroids42
5.2. Timescales of the space weathering processes 43
5.3. Dependency of spectral changes on starting materials 44
5.4. Summary 46
6. Conclusion 47
7. References 62

C-type asteroids are thought to be parent bodies of CM chondrites based on spectroscopic studies; C-type asteroids and CM chondrites both show similar reflectance spectra in Ultraviolet (UV) - visible (Vis) - near-infrared (NIR) range (e.g., Burbine et al., 2002; Hiroi et al., 1993, 1996; Lantz et al., 2013; Takir et al., 2013; Vilas, 1994; Vilas & Gaffey, 1989). On the other hand, spectroscopic observations indicated that C-type asteroidal spectra change bluer with surfaces aging (Nesvorný et al., 2005), probably due to space weathering. Several laboratory simulations have clarified the effects of space weathering on the Moon and S-type asteroids (Donaldson Hanna et al., 2015; Heiken et al., 1991; Pieters et al., 2000; Yamada et al., 1999). In particular, Hayabusa mission led by the Japan Aerospace Exploration Agency (JAXA) provided direct evidence for space weathering by Itokawa surface observation (Hiroi et al., 2006), and by Itokawa sample analyses (Noguchi et al., 2011, 2014; Tsuchiyama et al., 2011, 2014). About C-type asteroidal space weathering, little is known so far but several reproducing experiments using carbonaceous chondrites have been reported, i.e., ion irradiation experiments (Brunetto et al., 2014; Dukes et al., 2015; Lantz et al., 2015; Lantz et al., 2017; Vernazza et al., 2013), and pulse-laser irradiation experiments (Gillis-Davis et al., 2013, 2015, 2017; Matsuoka et al., 2015). In addition, telescopic observations also indicated that not a few C-type asteroids experienced dehydration to some extent. Some C-type asteroids, including Ryugu as the target body of Hayabusa2 mission led by JAXA, are thought to have been heated and dehydrated judging from their spectra which are slightly different from the spectra of fresh or space-weathered chondrites but similar to the spectra of experimentally-heated chondrites (Hiroi et al., 1993, 1996; Sugita et al., 2013). The spectra of Ryugu in Vis-IR range obtained by Hayabusa2 spacecraft are expected to clarify the relationship between C-type asteroids and carbonaceous chondrites in combination with mineralogical analyses of return samples, and will provide a strong constraint on the evolution process of early solar system.

In Chapter 1, micrometeoroid bombardments on the surfaces of C-type asteroids were demonstrated by pulse-laser irradiation experiments using Murchison CM2 chondrite. I aimed to describe effects of space weathering by micrometeoroids, especially focusing on the effect of energy set lower than the energy in the previous study (Matsuoka et al., 2015), whose energy range was 5–15 mJ. Pellet samples of Murchison was irradiated by the pulse laser with various intensities (0.7, 1, 2, and 5 mJ). The reflectance spectra of the irradiated samples were measured, and chemical compositions and micro-structures the surface of the laser-irradiated Murchison were analyzed. Due to laser heating, Murchison spectra show flattening and darkening in ultraviolet (UV) - visible (Vis) - infrared (IR) range. With increasing laser energy from 0.7 to 5 mJ, the 0.7- and 3-μm band depths decrease. The particle surfaces of 5-mJ irradiated area show melted and bubbled structures, which indicates the high-temperature heating by laser irradiation followed by rapid cooling. The chemical composition of the melted and bubbled portions is similar to FeS-rich amorphous silicate particles observed in the high-energy laser irradiation case. Each mineralogical change of Murchison due to short-duration heating would cause spectral bluing, darkening, and band depth decreasing. In conclusion, UV-Vis-IR spectra of Murchison samples irradiated with laser of 0.7–5 mJ show bluing, darkening, and depths decreasing of the 0.7- and 3-μm bands. These spectral changes are consistent with the change of Murchison spectra irradiated at 5–15 mJ in our previous study, other than successive darkening in spectra of low-energy irradiated Murchison. Serpentine dehydration and amorphization, and the deposition of melted FeS-rich particles generated by laser heating would cause spectral bluing and darkening. Darkening caused by serpentine dehydration and amorphization would be saturated by additional effect of albedo increasing, one is due to carbon content depletion by oxidation and the other is due to surface roughness development by dynamic melting during high-temperature short-duration heating.

In chapter 2, spectral and mineralogical analyses were performed using nine naturally-heated and dehydrated carbonaceous chondrite samples which classified into heating stages (HS) from I to IV based on X-ray diffraction results. In-situ heating of samples at 120–400 °C was performed during spectral measurements and successfully removed absorption water and part of rehydrated water from chondrite samples. Reflectance spectra of HS-I samples show the positive slope in visible (Vis)-infrared (IR) range and the large 0.7- and 3-μm absorption bands. The 0.7-μm band appears in only HS-I sample spectra. With increasing temperature of heating, (1) Vis-IR slope decreases, (2) the 3-μm band becomes shallower, and (3) Christiansen feature and Reststrahlen bands shift toward longer wavelength. TEM/EDX analyses showed that the matrix of strongly-heated chondrites consists of tiny olivine, low-Ca pyroxene, and FeNi-rich metallic particles mostly smaller than 100 nm in diameter, instead of Fe-rich serpentines and tochilinite observed in the HS-I chondrite. It is indicated that the Vis-IR spectral slope decreasing mainly due to decomposition of hydrous minerals, and the 0.7- and 3-μm band weakening proceed with progress of dehydration of hydrous minerals and formation of FeNi metal grains and secondary anhydrous silicates. In conclusion, in proportion to the heating degree, amorphization and dehydration of serpentines and tochilinite from HS-I to HS-II might cause the 0.7- and 3-μm band weakening, spectral slope decreasing, and albedo decreasing of chondrite spectra. In addition, formation of secondary olivine, pyroxene, and FeNi-rich metal grains at HS-IV would be responsible for the 3-μm band depth decreasing, spectral slope increasing, albedo increasing, Christiansen feature peak shift, and Reststrahlen bands changes of chondrite spectra.

At the surface of the C-type asteroids, a complex alteration could be proceeding due to micrometeoroid bombardments and solar-wind implantation as the space weathering, as well as solar radiation and impacts as heating events. For space weathering, first for ~10^3 years, solar wind implantation is effective for spectral changes as the 3-μm band depth increasing (Nakauchi, 2017). After that, micrometeoroid bombardments promote the 3-μm band depth decreasing, and simultaneously spectral flattening, darkening, the 0.7-μm band decreasing, and peak shifts of the Christiansen feature and the Reststrahlen bands. In parallel, constant solar-radiation heating and occasional impact events cause spectral changes of depth decreasing at 0.7- and 3-μm bands, albedo, slope changes, and Christiansen feature and Reststrahlen bands changes due to thermal alteration. Regolith gardening and impacts could reset the aging surface materials and expose the relatively fresh rocks, and also change the spectra to some extents.

別　紙

論文審査の結果の要旨

太陽系形成期の情報は、地球のような物質進化した天体には残されておらず、太陽系初期に形成されほぼそのままの状態で保存されている小惑星や彗星といった太陽系小天体にのみ残されている。したがって原始的な小惑星から地球に飛来する炭素質隕石は太陽系黎明期の情報を残しており、それらの隕石の物質科学的研究から太陽系の固体物質の初期進化過程が解明されてきた。一方、小惑星の表層物質は太陽風照射、微小ダスト衝突、他天体衝突などにより、大気のない微小天体に特徴的な物質進化をしてきたことが、地上からの観測で得られる小惑星の反射スペクトルの変化などにより確認されてきた。しかしながら、表層物質が物質科学的にどのように進化してきたのか、また、その物質進化と反射スペクトルの変化がどのように対応しているのかは不明であった。本博士論文は、小惑星表層における宇宙風化の物質化学変化を知るために、始原的な小惑星である C 型小惑星から飛来した炭素質隕石に対し、実験的にレーザー照射を行うことで微小隕石衝突による宇宙風化を再現した。また、小惑星上で加熱変成を受けた炭素質隕石の物質科学的研究を行い、小惑星上での衝突現象などによる加熱による物質変化と反射スペクトル変化の相関を調べた。

第１章では、宇宙風化作用の再現を目的として行った炭素質隕石を用いたレーザー照射実験の結果を示した。レーザー照射隕石試料に対し、反射スペクトル測定、 微細組織観察および化学組成分析を行った。スペクトルは照射エネルギーの増加に伴って青化、暗化、0.7-，3-μm帯弱化の進行を示した。また 5 mJ 照射試料表層における溶融発泡構造は、15 mJ 照射時採取した FeS に富む非晶質シリケイト飛沫粒子と類似の化学組成を示した。従って、レーザー照射により含水鉱物の非晶質化・脱水および FeS に富む非晶質シリケイト粒子の生成と再堆積が進行し、反射スペクトルにおける青化、暗化、吸収帯弱化が生じたことを明らかにした。

第２章では、加熱ステージ（HS-）Ⅰから IV（IV が最高温度）に分類される加熱脱水を経験した炭素質隕石を用いた反射スペクトル測定、 微細組織観察および化学組成分析の結果を示した。反射スペクトルにおける吸着水・復水の影響を減じるため、赤外分光測定において加熱測定を行った。この結果、HS-I から II へ含水鉱物の非晶質化と脱水が進行し、吸収帯弱化、傾きの減少および暗化が生じたことが示された。HS-IV では ２次無水鉱物および Fe, Ni に富む金属粒子の生成によって、傾き・反射率の増加および中間赤外域の変化が生じたことを明らかにした。

以上の研究結果により、宇宙風化作用および加熱脱水が並行して進行する C 型小惑星表層においては、表層面の形成後数百年間は太陽風照射による風化が卓越するが、その後は微小隕石衝突による風化が卓越し、3μm吸収帯弱化、青化および暗化が進行する。同時に散発する小天体衝突による加熱現象で、0.7 および 3μm吸収帯弱化、反射率・傾きおよび中間赤外域の変化が生じる一方で、レゴリスガーデニングや小天体衝突によってスペクトル変化がある程度初期化されると考えられる。これらの研究成果は、これまで不明だった C 型小惑星表層における物質進化過程を物質科学的に解明し、また反射スペクトルの変化を物質科学的に説明することに成功したという点で重要であると考えられる。

以上の内容は、本論文の提出者・松岡萌が、自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって、本博士論文は、博士（理学）の学位論文として合格と認める。