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研究成果の概要（和文）： Fe-Fe3S 系, Fe-S-Si 系、Fe-C 系 Fe-Fe3S 系、FeNiSi 合金、FeNiS 合金などの鉄・軽元素系について、地球核の高温高圧下において、相関係・溶融関係を明らかにした。また、放射光 X 線を用いて地球核の圧力条件において、Fe-軽元素系の状態方程式の決定、X 線非弾性散乱実験によって音速の測定、磁性およびスピン状態を決定した。特に、173 GPa 3000K という世界最高の温度圧力条件で鉄の音速の測定に成功した。以上の実験を総合して、地球核に含まれる軽元素組成、内核境界および核マントル境界の温度構造を明らかにした。

研究成果の概要（英文）: We determined the melting relations of Fe-S, Fe-C, Fe-H, Fe-Ni and Fe-S-Si, Fe-S-H systems, and compression of hcp-FeNiSi and hcp-FeNiS alloys, Fe_3S, and Fe_3C to the core conditions. We also successfully measured compressional velocity of hcp-iron to 173 GPa at 3000 K, which are the data determined at the highest pressure and temperature by the IXS method. We also determined the spin-state and magnetic properties of the iron-oxides and iron-light element compounds at high pressure. Based on these experimental results we proposed the model of the composition and the temperature profile of the core.

研究分野：数物系科学

キーワード：地球惑星物質、地球惑星進化、地殻・マントル・核、鉱物物理

１．研究開始当初の背景

地球中心部の核は極限の温度圧力条件にあり、この条件での実験的研究は非常に限られている。そのような内外の研究の現状に対して、本特別推進研究「地球惑星中心領域の超高圧物質科学」では、地球核の条件を実現し、地球核、核マントル境界、マントル深部の構成を解明することが不可欠である。

２．研究の目的

第一に地球核の温度圧力を実現し、圧力スケールを確立する。この研究では、核の条件であるマルチメガバールである地球の核の条件を実現し、その条件での圧力スケールを確立する。第二にスピン転移、磁気転移、構造相転移など地球・惑星中心部の様々な相転移現象を明らかにする。第三に核・下部マントル条件で地球物質の弾性波速度を測定し、密度と地震波速度を制約する地球中心部の物質モデルを創出する。

３．研究の方法

両面レーザー加熱ダイヤモンドアンビル装置と放射光を組み合わせて、世界をリードする手法開発しつつ、核を恒星ずる物質の相関係、状態方程式（密度）、弾性波速度、磁性・スピン状態を解明した。すなわち、X線粉末回折実験に加えて、非弾性性散乱(IXS)を用いて下部マントルと核を構成する物質の弾性波速度の測定を行った。これによって、地震学の直接観測量である地震波速度と直接比較対照を可能にした。さらに、我が国独自のエネルギー領域放射光 ^{57}Fe メスバウア分光システムを導入し、X線回折、放射光メスバウア併用システムを構築し、地球中心部を作るケイ酸塩高圧相や金属軽元素系化合物の鉄原子の価数、スピン状態、磁性を解明した。

４．研究成果

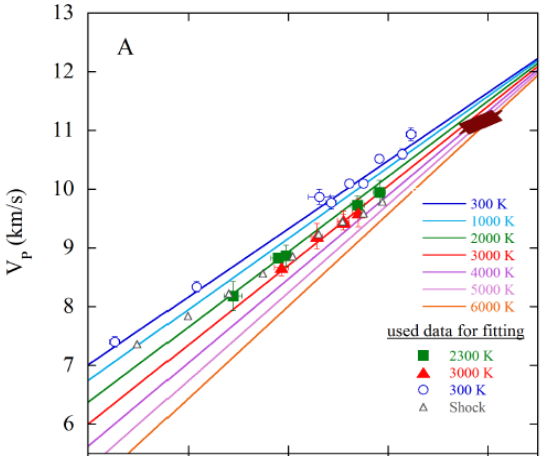
上記の研究計画のもとに、以下のような注目すべき重要な成果が得られ、これにもとづいて、地球中心核の物質科学的なモデルを提案した。

地球核の構造と物性: 核の圧力条件 P >250

GPa, T>3500 K の条件を実現し、内核を構成する金属珪素合金の安定相と融点を解明し、圧縮特性を明らかにした。Fe-Fe_3S 系の融点を 180 GPa 程度まで決定した。また地球の中心を越える 374GPa で 700K を実現し、FeNiSi 合金、FeNiS 合金の状態方程式を内核の圧力まで明らかにした。これらは、核の研究としては、世界初の成果である。また、Fe-S-Si 系、Fe-C 系の融点を 200 GPa までの圧力で測定を行った。これらの鉄—軽元素系の融点にもとづいて、内核境界と核マントル境界の温度を推定した。

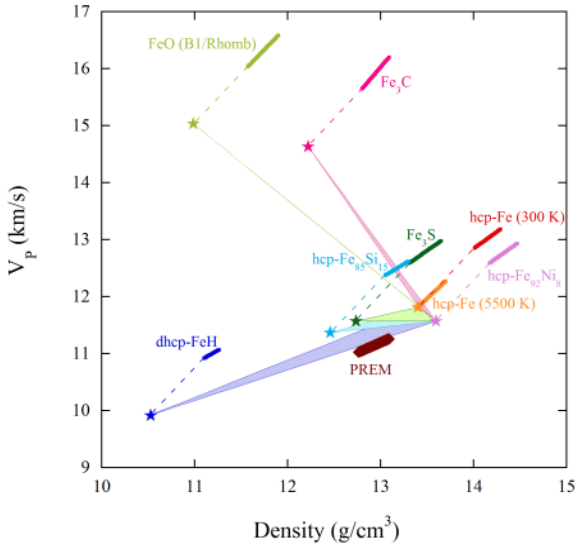
地球核物質の音速測定：Spring-8 の BL35XU において、173GPa で 3000K までの条件で、地球核物質である hcp-Fe の縦波速度と音速測定に成功した。図は実験で得られた縦波速度と密度の関係を地震波モデル（PREM）と比較したもの。これは、金属鉄の音速測定としては、世界最高の圧力での測定である。Fe3S については室温で 50GPa まで、また FeH に関しては室温で 70GPa まで、Fe_3C については 100GPa までの測定に成功した。

図 1 ：173 GPa, 3000 K までの条件で得られた縦波速度と密度の関係



地球中心部の物質科学的モデルの提案：

図 2. 地球の内核（PREM）と内核温度圧力条件での鉄および鉄軽元素化合物の音速と密度



Hcp-Fe について縦波速度と密度の関係を 173GPa, 3000K まで測定し、縦波速度・密度関係の温度依存性を明らかにした。さらに世界で初めて音速・密度関係の温度依存性を明らかした。鉄・軽元素系の縦波速度・密度関係が、今回測定したε-Fe のものと同じであると仮定して、音速・密度関係を得た（図 2）。

地震波プロファイルの PREM と比較して、内核の軽元素として、水素・ケイ素・硫黄が有力であり、酸素、炭素の可能性は小さいことを明らかにした。

地球内部の炭素・水循環: 下部マントルでの揮発性成分物質の振る舞いを解明するために、MgSiAlOOH の含水 H 相の平衡関係を明らかにした。この相は、沈み込むプレート内に存在し、水素を核マントル境界に輸送することを明らかにした。水素とともに炭素の振る舞いに関しても $MgCO_3$-SiO_2 系の相関係を解明し、80-100 GPa の限られた圧力条件でのみ、ダイヤモンドが生成することを示し、下部マントル由来のダイヤモンドが生成しやすい下部マントルの深さを明らかにした。

５．主な発表論文等

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その他 72 件、総計 126 件（査読有 124 件）

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（講演総数 547 件うち招待講演 34 件）

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6. M. Murakami , (invited) Elastic wave velocity measurement under ultrahigh-pressure using Brillouin scattering spectroscopy. 39th Seminar for High-Pressure Science and Technology. 東京, 3 月 26 日, 2014.
7. Ohtani E, (invited) Water at CMB and light elements in core. D" layer symposium. 鳥取, 3 月 22 日, 2014.
8. Sakamaki T, Ohtani E., Fukui H.., Kamada S., Takahashi S., Sakairi T., Takahata A., Sakai T.., Tsutsui S., Baron A. Q. R. (invited), Sound velocity of iron up to 160 Gigapascals and 3000 Kelvin. Workshop on Elasticity and Iron, Hyogo, February 25-27, 2014.
9. Ohtani E., Sakamaki T., Kamada S., Fukui H.., Shibazaki Y., Takahashi S., Sakai T.., Tsutsui S., Baron A. Q. R., (invited), Sound velocity measurements of iron-light element alloys: A challenge to the core conditions. Workshop on Elasticity and Iron, Hyogo, February 25-27, 2014.
10. Kamada S., Ohtani E., Fukui H.., Sakai T.., Terasaki H.., Shibazaki Y., Tsutsui S., Baron A. Q. R., Hirao N.., Ohishi Y., (invited), Vp and EOS of Fe_3S. Workshop on Elasticity and Iron, Hyogo, February 25-27, 2014.
11. Ohtani E, (invited), Water transport into the core-mantle boundary region of terrestrial planets. AGU Fall meeting 2013, San Francisco, December 9-13, 2013.
12. M. Murakami, (invited), Spectroscopic evidence for new denser structure in silica glass under ultrahigh pressure. AGU Fall meeting 2013, San Francisco, December 9-13, 2013.
13. M. Murakami, (invited), Radiative conductivity of dense silicate metls at core-mantle boundary. Workshop on Particle Geophysics, Sendai, October 29, 2013.
14. Ohtani E (Invited). Phase relations and physical properties of iron alloys at high pressure: approach to the Earth's core. III International conference Crystallo-genesis and Mineralogy, Russia, September 27- October 1, 2013.
15. Ohtani E. (invited), Sound velocity and density of iron alloys and metallic melts at high pressure and their geological implication. XV Liquid and Amorphous metals Conference, Beijing, Sep 16-20, 2013.
16. M. Murakami, (Keynote), Structure of silica glass under ultrahigh-pressure. Goldschmidt 2013, Florence, Italy, August 25-30, 2013.
17. M. Murakami, (invited), Spectroscopic evidence for ultrahigh-pressure polymorphism in silicate glasses. The 7th International Discussion Meeting on Relaxations in Complex Systems 2013. Barcelona, July 22, 2013.
18. Terasaki H.., (invited), Measurements on physical properties of liquid alloys under high pressure. Paris-Edinburgh Cell workshop, Chicago, May 23-25, 2013.
19. El Goresy A., Gillet F., Miyahara M.., Ohtani E., Ozawa S., Lin Y., Feng L., Escerig S., (invited), Tissint is a Rosetta stone deciphering Noachian magmatic activities and dynamic events in mars young history. Japan Geoscience Union Meeting 2013, Chiba, May 20-25, 2013.
20. Ohtani E. (invited), Phase relations and

sound velocity of iron and iron-sulfur system at high pressure: implications for the Earth's inner core. Seoul National University, Seoul, November 13-16, 2012.

21. Ohtani E. (Invited), Transport of volatiles into the deep Earth. School of Earth and Environmental Science. Seoul National University, Seoul, November 13-16, 2012.
22. Sakai T.., Ohtani E., Hirao N.., (keynote) Equation of state of Fe-Ni Alloy at multi-megabar pressure. Joint 2012 COMPRES Annual Meeting and High-Pressure Mineral Physics Seminar-8, Lake Tahoe, USA, July 9-13, 2012.
23. Ohtani E. (invited) Phase relations and Physical properties of the Earth's core. Joint symposium of Misasa-2012 and Geofluid-2, Misasa, March 18-21, 2012.
24. Sakai T.., Ohtani E., Terasaki H., Kamada S., Hirao N..(invited) Sulfur content in the core. Joint symposium of Misasa-2012 and Geofluid-2, Misasa, March 18-21, 2012.
25. Terasaki H.., Urakawa S., Rubie DC., Funakoshi K., Sakamaki T., Shibazaki Y., Ozawa S., Ohtani E. (invited) Droplet size of liquid Fe-alloy in terrestrial magma ocean. Joint symposium, Misasa-2012 and Geofluid-2, Misasa, March 18-21, 2012.
26. Ohtani E., Sakai T., Kamada S., Fukui H.., Shibazaki Y., Baron Alfred Q.R., Tsutsui S., Asanuma H. (Invited). Phase relations density and sound velocity of Fe-Ni-Si alloys and composition of the inner core. 2011 GSA Annual meeting, Minneapolis, October 9-12, 2011.
27. Ohtani E. (Invited). Carbon and light elements in planetary cores. "Deep Carbon Observatory" Deep Carbon Cycle International Workshop (DCO-3), Altai Russia, August 25-30, 2011.
28. Ohtani E., Zhao D., Kuritani T., Tajima FC. (invited). Deep dehydration and physical and chemical nature of the mantle above the stagnant slab. 2010 AGU Fall Meeting, San Francisco, December 13-17, 2010.
29. Ohtani E. (invited) Composition, physical properties and thermal state of the core. CECAM 2010 (Computational Mineral Physics: Applications to Geophysics), Zurich, Switzerland, October 11-15, 2010.
30. Sakai T., Ohtani E., Terasaki H., Kamada S., Hirao N., Sata N., Ohishi Y. (invited) Compression of Fe-Ni-S alloy up to the pressure of the center of the Earth. IMA 2010 (The 20th general meeting of the international mineralogical association), Budapest, Hungary, August 21-27, 2010.
31. Ohtani E. (Invited), Chemical and physical properties and thermal state of the core and lower mantle, The 12th Symposium of SEDI （Study of the Earth's Deep Interior), Santa Barbara, California, July 18-23, 2010.
32. Ohtani, E., (Invited), Application of in situ X-ray observations to melting and melt properties at high pressure. Goldschmidt conference, Knoxville, Tennessee, June 13-18, 2010.
33. Ohtani, E. (invited). Iron-Silicate Reactions and Light Elements in the Core. Invited Lecture at Chin. Acad. Sci., April 21-25, 2010.

招待講演 33 件その他 513 件：講演総数 547 件

〔その他〕
ホームページ等
http://www.ganko.tohoku.ac.jp/bussei/newHP/busseiHP/tokusuiHP_22-26/index.html

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