Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SIT39-01 会場:416 時間:5 月 2 日 09:00-09:15

マックスウェル粘弾性体の力学方程式の新しい定式化
A new form of the dynamics equation of Maxwellian visco-elastic media

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岩石からなる地殻・マントルやグリーンランド・南極に存在する氷床は普通の意味で固体であるにもかかわらず、長い時間スケールでは流動することが知られている。そして、マントル対流などに対しては粘性流体とみなして Navier-Stokes 方程式を基に数値シミュレ-ションが行われている。氷床流動に関しても氷は粘性流体として扱われ、ただ粘性力と流れの関係が非ニュートン的とされている。

一方、両方の性質を考慮しなくてはならない問題として、氷期終了後の地殻上昇の問題では、応力とひずみの関係を表す構成方程式として、Maxwell によって提唱された短い時間では弾性体、長い時間では粘性流体となるような形の式を用いて議論されてきた。しかし、この方程式を用いた議論は、伝統的に時間に関してラプラス変換して半ば解析的に扱われてきた。これを、ちょうど大気や海洋の大循環の数値シミュレーションのように、時間空間差分化して解こうとするとうまくいかない。

そのような背景のもと、マントル対流のシミュレーションで、地表近くの弾性体としてのプレートの効果を取り込むことは大変困難であり、うまくできていない。氷床流動でも、西南極大陸で岩盤を離れて海水の上に張り出した氷棚を粘性流体として扱うのには疑問がある。「正しい」粘弾性体力学を基に両方の性質を持ち、時間空間差分化した数値シミュレーションを可能とする方程式の形をさぐる。

マックスウェルの構成方程式は、ばねとダッシュポットが直列につながれた系の示す力と変位（のび）の関係をモデルとして導かれた。この系で、ダッシュポットの部分は粘性を表すと考えられ模式図にもそのように描かれる。しかし、系の力は一つだから、ばねの伸びだけできまり、ダッシュポットの部分はばねの伸び縮みの原点の位置の時間的変化を表す式と考えてもかまわない。その結果、力が等しいという関係式はばねの原点（自然長は不変）がばねの伸び縮みによって引きずられて変化する事を表す式と読み替えられる。これを連続体における力と歪の関係に置き換えると、弾性歪を定義する原点の位置（のひずみ）即ち塑性歪の時間変化が弾性歪によって生じる事を示す式となる。即ち弾性歪が時とともに塑性歪に転化すると言う事を意味する。この時定数がマックスウェル緩和時間になる。

こう考えると、日常経験的にも知られている「弾性ひずみが時とともに塑性ひずみに転化する」という事を物理の法則とし、これと弾性体に対する運動方程式とを組み合わせて基礎方程式系とする事が適切と思われる。このことは従来の「正しい」マックスウェル構成方程式と矛盾せず、差分法による数値積分を可能にする。即ち、弾性波の伝搬より十分ゆっくりの現象に対しては（静的）準弾性平衡を保ちつつ、「弾性ひずみ緩和」によって生じるゆっくりした変化を扱うのである。

マントル対流を粘性流体として扱いつつ、地球表面近くのプレートの弾性を取り入れようとする試みが、過去２０年ほど現れてきたが、著者が調べた範囲では工学のレオロジーで使われた方程式系をそのまま持ってきたもので正しいものではない。

キーワード: マックスウェル粘弾性体, 粘弾性体力学, マントル対流, プレート・マントル結合シミュレーション
Keywords: Maxwellian visco-elsatic media, visco-elastic medium dynamics, mantle convection, plate-mantle coupling simulation

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SIT39-02 会場:416 時間:5 月 2 日 09:15-09:30

斜方輝石－カンラン石間の水の分配に与える Al の効果：リソスフェアーアセノスフェア境界に関する考察

Effects of Al content on water partitioning between Opx and Ol: Implications for lithosphere-asthenosphere boundary

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Most minerals in the Earth's upper mantle contain small amounts of hydrogen (i.e. "water"), structurally bound as hydroxyl. Water has an important influence on the behavior of rock system. This small amount of water has an important influence on the behaviours of rock systems. A large viscosity contrast of more than two orders of magnitude was detected at depths of 70 km to 100 km beneath ocean and was defined as the lithosphere-asthenosphere boundary [1]. The origin of the lithosphere-asthenosphere boundary remains an enigma. The water distribution in the Earth is critical to the nature of the boundary. For example, Mierdel et al. (2007)[2] indicated that a high water solubility in aluminous orthopyroxene among mantle geotherm in the Earth's upper mantle would effectively contribute to a stiffening of the lithosphere. Therefore, precise knowledge on the distribution of water among mantle minerals is very important for understanding the Earth's dynamics. The Earth's uppermost mantle is composed mainly of olivine (Ol), orthopyroxene (Opx), clinopyroxene (Cpx), spinel, and garnet. In particular, Ol accounts for a large proportion (60 vol.%) of the Earth's uppermost mantle. In addition, Opx, which contains significantly more water than does Ol in the mantle xenolith, is the second phase of the Earth's uppermost mantle. The FeO content in mantle Ol shows very limited variation in range, whereas the Al content of Opx in the Earth's upper mantle decreases significantly with increasing pressure [3] Therefore, the variation of Al content in mantle minerals can be important for the solubility of water in mantle minerals.

To investigate the partitioning coefficient of water between Opx and Ol ($D_{(Opx/Ol)}$) under low-water concentrations (3 ~ 387 wt. ppm) similar to the Earth's mantle conditions, high-pressure experiments have been conducted at pressures of 1.5-6 GPa and a temperature of 1573 K. The experiments were performed with Kawai-type multi-anvil and piston-cylinder apparatus by using starting materials of natural Ol and synthetic Opx with various Al contents. The water contents were obtained with a vacuum type Fourier transform infrared spectrometer (*Jasco*: FT-IR6100, IRT5000). Water content of minerals was calculated based on Paterson's calibration [4]. IR-spectra of Ol and Al-bearing Opx in this study are similar to those obtained by high-pressure experiments [5] and natural rocks [6], respectively. It is believed that broad bands in IR spectra of natural Opx are due to effect of crystal distortion by large Al substitution. On the contrary, IR-spectra of Al-free Opx are not consistent with those reported by Rauch and Keppler (2002) [7] likely because of the large difference of water fugacity. $D_{(Al-freeOpx/Ol)}$ is ~ 1 at all pressure conditions. However, the water contents of Al-bearing Opx are significantly larger than those of Ol at the same conditions. In addition, the effect of Al concentration in Opx on $D_{(Opx/Ol)}$ becomes larger with increasing pressure. The high Al content in Opx significantly increases $D_{(Opx/Ol)}$ and the trend increases with increasing pressure. $D_{(Opx/Ol)}$ drops sharply at the pressure at which the Al concentration of Opx becomes nearly 0 in the Earth's mantle conditions.

These results imply that viscosity of the upper mantle decreases sharply at depths deeper than those in which orthopyroxene contains no Al. The dramatic change of $D_{(Opx/Ol)}$ may explain the lithosphere-asthenosphere boundary beneath oceans and continents.

[1] D.L. Anderson, (1989) Blackwell Scientific, Boston [2] K. Mierdel et al. (2007) Science, 315, 364-368 [3] M. Obata, (1976) Am. Mineral., 61, 804-816 [4] M. S. Paterson, (1982) Bull. Mineral., 105, 20-19 [5] Q. Bai and D.L. Kohlsted, (1993) Phys. Chem. Minerals, 19, 460-471 [6] K. Grant et al., (2007) Contrib Mineral Petrol, 154, 15-34 [7] M. Rauch, H. Keppler, (2002) Contrib. Mineral. Petrol., 143, 525-536

キーワード: 水の分配係数, カンラン石, 斜方輝石, 粘性, FT-IR, リソスフェアーアセノスフェア境界
Keywords: water partitioning coefficient, olivine, orthopyroxene, viscosity, FT-IR, lithosphereasthenosphere

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SIT39-03 会場:416 時間:5 月 2 日 09:30-09:45

Brillouin 散乱分光法に基づく高圧力条件下での非晶質 MgGeO3 の構造変化の研究
Acoustic velocities of MgGeO3 gel at high pressure by Brillouin scattering

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Properties of silicate melts are essential for understanding evolution and dynamic behavior of the Earth and terrestrial planets. In the shallow mantle melting processes the density contrast between melts and crystals is well studied, but studies on the deep melting near the core-mantle boundary are still limited due to technical difficulties. The studies of amorphous material, analogs of melt, at high pressure can provide valuable insights about melts in the deep mantle. The Brillouin scattering method is suitable for velocity measurements of amorphous materials. It has been suggested that the change in coordination in the melt or glass structure reflects to the change in acoustic velocity. Thus we conducted sound velocity measurement using the Brillouin scattering method in diamond anvil cell at high pressure. We report in situ high-pressure acoustic velocity measurements of $MgGeO_3$ gel, an analogue of the $MgSiO_3$ melt, revealing the gradual coordination change of Ge from four- to six at least up to 80 GPa. We will conduct experiments at higher pressure in order to confirm the possible Ge coordination change in the gel expected to exist in the terrestrial and extraterrestrial planets.
Keywords: sound velocity measurement, high-pressure experiment, mantle dynamics, silicate melts, super-Earth

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SIT39-04 会場:416 時間:5 月 2 日 09:45-10:00

海洋多重反射波補正した広帯域海底地震計間 P 波相対走時測定
Measurement of differential P-wave travel time between two BBOBSs with Correction for crustal reverberation

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マントル３次元地震波速度構造の推定において海洋での観測が全球的に解像するのに欠かせない。しかしながら、海底での地震観測は一般的に周期５秒以下でノイズレベルが高いため、相の立ち上がりを読むことは困難である。そこで、約 10 秒またはそれ以上の周期帯で波形相関をとり、２観測点間の相対的な走時を測定することが行われている（例えば、Toomey et al. 1998, Tanaka et al., 2009）。

一方、P 波マントルトモグラフィーにおいて、P 波走時の分散を有限波長理論を用いてインバージョンに取り入れることは、分解能の向上に有効であり（例えば Obayashi et al. 2013 JpGU meeting）、観測点の少ない海洋下では特に大きな効果が期待される。Obayashi et al.（2004）は PP 波が反射点下の（海洋を含む）地殻多重反射波の影響で分散が生じることを示した。直達 P 波でも観測点下の地殻多重反射の影響はあり、特に海洋の多重反射の影響は無視できない。大林ら (2012) は地球深部構造由来の分散を広帯域海底地震計で測定すべく、堆積層を含む海洋多重反射の影響を補正する方法を提案した。それはまず堆積層を含む地殻構造および水深から Haskell のマトリックス法を用いて、観測点下の多重反射の応答を計算し、多重反射応答を互いの観測波形に畳み込み積分し、波形相関により相対走時を測定するというものであった。その際に堆積層の構造が多重反射波の波形に大きな影響を与えるため、堆積層構造の推定が重要であることを報告した。しかしながら、その後の検討の結果、堆積層が 1 km 未満と比較的薄い場合には、走時の測定においては構造の多少の違いはほとんど影響がないことが判明した。

そこで、我々はフレンチポリネシアに展開した広帯域海底地震計に上記測定法を適用した。BBOBS と島の観測点間の波形は補正を施すことでたがいに似るようになり、補正法有効であることを示している。観測された分散の特徴と分散データを取り入れたトモグラフィーの初期結果を報告する。

キーワード: 地殻多重反射, 広帯域海底地震計, トモグラフィー
Keywords: crustal reverberation, broadband ocean bottom seismometer, tomography

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SIT39-05 会場:416 時間:5 月 2 日 10:00-10:15

立方晶カルシウムペロブスカイトの小さな剛性率
Small shear modulus of cubic CaSiO3 perovskite

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Ca-perovskite (CaPv) is considered to be one of the most abundant minerals in the Earth's lower mantle (LM) and was suggested to have distinctly larger shear modulus than MgPv from static calculations and mean-field theory (Karki and Stixrude 1999; Stixrude et al. 2007). In this study the elasticity of cubic CaPv is reinvestigated using density functional constant-temperature first principles molecular dynamics simulations with strict calculation conditions. First, we computed the stable structure of CaPv and found that the cubic phase is more stable than the tetragonal and orthorhombic in the LM P,T condition. The thermal equation of state of CaPv was analyzed using the MD data set, which indicates its thermal properties including Gruneisen parameter quite similar to those of MgPv. Along the adiabatic temperature, CaPv was found to have higher density than the PREM and 12.5% iron-bearing MgPv. Next, we calculated elastic constants of cubic CaPv. Our new results clearly demonstrate that cubic CaPv does not have anomalously large shear modulus suggested by previous calculations with a small computation cell. This is because the cell applied in the previous studies is too small to allow the rotational phonon motion of SiO6 octahedra related to the zone boundary optic phonon instability. Acoustic wave velocities were finally determined from the elastic moduli, indicating no significant differences in velocities between CaPv and iron-bearing MgPv.

キーワード: Ca ペロブスカイト, 弾性率, 下部マントル, 第一原理計算
Keywords: Ca-perovskite, elasticity, lower mantle, first principles

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SIT39-06 会場:416 時間:5 月 2 日 10:15-10:30

Seismic Constraints on an Enstatite Chondrite Earth
Seismic Constraints on an Enstatite Chondrite Earth

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Recently, Javoy et al., EPSL, 2010 suggested the possibility that Earth had an initial enstatite chondrite composition due to their similar oxygen isotopes. Currently, the calculations of the bulk silicate Earth (BSE) are based on the assumption that the initial Earth began with a composition very close to that of a carbonaceous chondrite. Thus, it is necessary to evaluate whether the 1D seismic properties of the Earth are more consistent with an initial enstatite or chondritic composition. The BSE of an enstatite chondrite Earth (ECE) is different from that of a carbonaceous chondrite since the magnesium/silicon ratio is much lower for the former, resulting in a lower mantle that is almost devoid of Mg. Hence, the primitive lower mantle of an ECE consists mostly of iron-rich perovskite and pure silica. The seismic velocities of these phases are much slower than Mg-perovskite which, by itself, is faster than PREM (the slower MgO phase is necessary to match PREM velocities). However, the present-day lower mantle would be a mix of the primitive upper mantle (ie. pyrolite) and the Mg-depleted lower mantle. The latest mineral physics results are used to calculate possible 1-D seismic profiles of the Earth associated with these two scenarios and to compare with those observed for the Earth today.

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SIT39-07 会場:416 時間:5 月 2 日 10:30-10:45

核マントル境界の熱特性モデリング
Thermal property modeling of the core-mantle boundary

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Lattice thermal conductivity of minerals under pressure and temperature is a key property to understanding dynamics and evolution of the Earth's interior. We recently established an efficient ab initio technique for calculating the thermal conductivity of silicate minerals with complex structure and chemistry (Dekura, Tsuchiya, Tsuchiya, PRL, 2013). Calculated lattice thermal conductivity of MgSiO3 perovskite agreed satisfactorily with experimental values at room temperature, and post-perovskite was found to have thermal conductivity quite different from perovskite's, indicating that the D" discontinuity is not only the phase transition boundary but also the conductivity boundary. Using the obtained results, we determine the effective conductivity of the lower mantle and estimate the energy flow across the core-mantle boundary (CMB). Our results demonstrate that the CMB heat flux could change significantly from place to place by reflecting temperature heterogeneity located atop the core. A large CMB heat flow recently suggested from the outer core side can be reconciled only by considering polycrystalline assemblages yielding high-thermal conductivity.

キーワード: 第一原理計算, 格子熱伝導率, CMB 熱流量
Keywords: First principles computation, Thermal conductivity, CMB heat flow

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SIT39-08 会場:416 時間:5 月 2 日 11:00-11:15

西太平洋下のD”領域内部の３次元S波速度構造
Waveform inversion for localized 3-D seismic velocity structure in the lowermost mantle beneath the Western Pacific

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We infer 3-D localized shear velocity structure in the lowermost 400 km of the mantle at the western edge of the Pacific large low shear velocity province (LLSVP) by applying waveform inversion to transverse component body-wave waveforms from the F-net seismic array in Japan. Our dataset consists of relatively long period (12.5-200 s) broad-band seismic waveforms of Tonga-Fiji deep focus and intermediate deep earthquakes. We conduct several tests to confirm the robustness of the inversion results. We find two low velocity zones at the bottom of the target region, with a high velocity zone in the middle, and a low velocity zone above the high velocity zone and contiguous with the two deeper low velocity zones at a depth of 200-300 km above the CMB. This supports the idea that the Pacific LLSVP may be an aggregation of small upwelling plumes rather than a single large thermochemical pile.

キーワード: 波形インバージョン, 西太平洋, マントル対流, 最下部マントル, プルームクラスター
Keywords: Waveform inversion, Western Pacific, Mantle convection, Lowermost mantle, Plume cluster

Japan Geoscience Union Meeting 2014
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SIT39-09 会場:416 時間:5 月 2 日 11:15-11:30

核条件下での hcp-Fe の音速・密度測定
Compressional sound velocity and density measurements of hcp-Fe under core conditions

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SAKAMAKI, Tatsuya[1*] ; OHTANI, Eiji[1] ; FUKUI, Hiroshi[2] ; KAMADA, Seiji[1] ; TAKAHASHI, Suguru[1] ; SAKAIRI, Takanori[1] ; TAKAHATA, Akihiro[1] ; SAKAI, Takeshi[4] ; TSUTSUI, Satoshi[5] ; BARON, Alfred[3]

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Sound velocity measurements of Fe and Fe-alloy at high temperature and high pressure are necessary to understand the Earth's inner core. Despite seismological observations providing density-sound velocity data of Earth's core, there are few experimental reports about sound velocity of hcp-Fe at ultrahigh pressure and temperature conditions. In order to push forward with research, we have developed a portable laser-heating system for diamond anvil cell, which is called COMPAT (Fukui et al., 2013). We have succeeded in measuring the sound velocity of hcp-iron up to 160 GPa and 3000 K by inelastic X-ray scattering measurements combining with a laser-heated diamond anvil cell. The obtained pressure and temperature dependence of the sound velocity suggest that compressional sound velocity of hcp-Fe at inner core boundary (330 GPa and 5500 K) is higher than that of Earth's inner core. Thus, we can conclude that the light elements or combination of the light elements and nickel in the inner core decreases both density and compressional sound velocity of hcp-Fe simultaneously under the inner core conditions.

Reference
Fukui et al., 2013. A compact system for generating extreme pressures and temperatures: An application of laser-heated diamond anvil cell to inelastic X-ray scattering. Review of Scientific Instruments 84, 113902; doi: 10.1063/1.4826497.

キーワード: 地球核, 音速, 密度, 高温高圧, X 線非弾性散乱, レーザー加熱式ダイヤモンドアンビルセル
Keywords: Earth's core, sound velocity, density, high pressure and high temperature, inelastic X-ray scattering, laser-heated diamond anvil cell

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SIT39-10 会場:416 時間:5 月 2 日 11:30-11:45

第一原理分子動力学法による鉄・軽元素系液体合金の状態方程式の決定
The P-V-T equation of state of liquid pure Fe and Fe-light elements alloys by ab initio molecular dynamics simulations

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The equation of state (EoS) of pure Fe and Fe-light elements alloy liquids were calculated by means of ab initio molecular dynamics simulations at the outer core *P*-*T* conditions. In the outer core, many light elements, such as carbon, nitrogen, oxygen, hydrogen, sulfur, and silicon, have been proposed as possible constituents. The concentrations of these elements have been strongly debated for years. In this study, internally consistent thermodynamic and elastic properties of pure Fe and Fe-light elements alloys, in particular density, adiabatic bulk modulus, and P-wave velocity were analyzed in order to clarify the effect of light elements incorporation on seismically observable data. Then the results were compared with the seismological data of the Earth's outer core to confine the plausible compositions of the outer core. The new EoS model of liquid iron alloys as a function of pressure, temperature and fraction of light elements may serve as fundamental data for the composition model of the Earth's core.

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SIT39-11 会場:416 時間:5 月 2 日 11:45-12:00

X 線吸収法と超音波法を併用した高圧下における Fe-C 融体の密度-弾性波同時測定
Simultaneous measurement of liquid Fe-C density and sound velocity at high pressure

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水星や火星、月といった地球型惑星および衛星の液体核は軽元素を含有した鉄合金融体で構成されていると考えられており、これら天体核の組成を解明する為には高温高圧下における鉄融体の密度や体積弾性率に対する軽元素の影響を定量的に評価することが必要となる。このような密度の情報に加え核中の軽元素を特定するためには、地震波速度データと直接比較できる弾性波速度の情報が不可欠である。本研究では弾性波速度測定の手法を SPring-8 BL22XU の装置に新たに導入し、高圧下における鉄合金融体の弾性波速度ー密度の同時測定を行った。

高温高圧実験は BL22XU 設置の 180ton キュービックマルチアンビルプレスを用いた。弾性波測定は超音波法 (Higo et al., 2009)、密度測定は X 線密度吸収法 (Katayama et al., 1993) を用いた。圧力と温度の測定は試料部に封入した MgO と h-BN 混合粉末の X 線回折パターンから格子体積を求め、2 つの圧力マーカーより圧力ー温度条件を算出した。

今回の測定では Fe-3.5wt%C 組成での測定を行った。圧力・温度条件は 2.9 GPa, 1850 K までの測定を行った。その結果、X 線吸収法により求めた密度の値は 1.2 GPa, 1675 K では 7.01 g/cm^3, 2.9 GPa, 1700 K では 7.15 g/cm^3 となり圧力とともに密度の上昇が観察された。この結果はこれまで我々が得ている X 線吸収密度法の結果 (Shimoyama et al., 2013) と調和的な結果であった。また超音波法による測定では試料の前面、背面からの反射波をはっきり観察することができ、得られた Fe-C 融体の縦波速度 V_P は、圧力と共に増加する傾向が見られた

キーワード: 密度, 弾性波速度, Fe-C 融体
Keywords: Density, Sound velocity, liquid Fe-C

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レーザー衝撃圧縮による液体状態での FeSi の音速密度測定
Sound velocity and density measurement of liquid FeSi alloy by laser-shock compression

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The internal structure of the earth is estimated by observing seismic wave. Comparing seismic wave observations and experimental data of sound velocity of iron(Fe), the composition of the Earth's core is not pure Fe. Several light elements (hydrogen, carbon, oxygen, silicon, sulphur, etc.) have been considered as the candidate of the composition of the Earth's core, but its composition is still unclear. In order to constrain the core composition, it is important to measure the sound velocity of iron alloys because it can be directly compared with the seismic wave. Silicon (Si) has been proposed as a major light element in the inner core [Mao et al., 2012]. So we measured the sound velocity of laser-shocked FeSi alloy in order to investigate the effect of Si for sound velocity of liquid Fe in the outer core condition.

The starting sample was prepared by synthesizing from mixture of Fe (99.98% purity) and Si (99.9% purity) slugs at arc furnace. The compositions of Fe and Si are 66.5 wt.% and 33.5 wt.%, respectively. We measured sound velocities and densities of FeSi at high pressure and high temperature conditions at the large laser facility in Institute of Laser Engineering, Osaka University. The sound velocities were measured by the x-ray radiography [Shigemori et al., 2012].

We obtained the sound velocity and density of FeSi at pressures around 700 GPa. It is seen that Si has the effect of increasing the sound velocity of liquid Fe. Comparing our experimental results and PREM model [Dziewonski and Anderson, 1981], Si may be contained up to 13.1 wt.% at 135 GPa, and up to 5.5 wt.% at 330 GPa in the outer core.