人工的に衝撃圧縮したコンドライト隕石の希ガス脱ガス過程

The degassing process of rare gases in chondritic meteorites during experimental shock compression

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　形成初期の太陽系において頻発していたと考えられる小天体間の衝突現象で，始源的小天体の構成物質が物理化学的に強い影響を受けていたことが明らかになっている．本研究では揮発性元素の一つである希ガスが，衝撃により小天体の構成物質からどの程度脱ガスされるかを知る目的で，小天体の一部であったと考えられるコンドライト隕石に対し一段式衝撃銃を用い30，47，70GPaで衝撃圧縮実験を行い，その回収試料に含まれる希ガス濃度の定量分析を行った．

　隕石にはさまざまな起源の希ガスが含まれていることが知られているが，そのうち太陽系形成初期（45.6億年前から約1000万年）に小天体の構成物質に含まれていた希ガスは，大部分が原始成分の希ガスであったと考えられる．その時期には放射壊変起源の希ガスは，一部（129Xe　from　129I，136Xe from 244Pu）を除き，半減期が長いためほとんど存在していなかったと考えられる．同様に宇宙線照射や太陽風起源の希ガスは小天体表層に偏在するため，小天体内部にはあまり存在していなかったと考えることができる．したがって，太陽系形成初期の衝突現象による小天体からの希ガス脱ガス過程を知るには，原始成分の希ガス量が小天体の構成物質であった始源隕石から，衝撃によってどのように失われていくかを調べれば良いことになる．

　原始成分の希ガスの主成分には2種類あって，それぞれQガスとHLガスと命名されている．QガスはAr，Kr，Xeといった重い希ガスの大部分を占め，それに対しHLガスはNe，Heといった軽い希ガスの大部分を占める．衝撃を与えていないアエンデ隕石と30，47，70GPaの衝撃を与えたアエンデ隕石計4つの試料について，長尾先生のご指導のもと，希ガス質量分析計を用いて希ガス量と同位体比を分析した．その結果，原始成分のAr，Kr，Xeといった重い希ガスは，衝撃圧の増加とともに減少し，70GPaの試料では衝撃を与えていないアエンデ隕石に比べ約75%脱ガスしていることがわかった．一方，原始成分のNe，Heは衝撃圧の強弱にかかわらず常にほぼ一定のガス量を保っていることがわかった．この結果は，始源隕石中の希ガス原始成分は衝撃をうけると，軽い希ガス（HLガス）はとどまり重い希ガス〈Qガス〉が選択的に脱ガスされるといった元素分別を引き起こすということを示している．このことは，脱ガスされ始源隕石から出ていった希ガスは，重い希ガスに富むことを示唆する．

　それではなぜ衝撃を受けると，軽い希ガスは隕石中にとどまり重い希ガスは失わ れるという現象が起こるのであろうか？それは原始成分の希ガスの担体の違いに起因していると思われる．Qガスは始源隕石中に～2%含まれる分子量の大きいQフェイズと呼ばれる炭化水素（ケロジェン化合物）の表面に保持されていると考えられており，それに対しHLガスは，始源隕石中に～500ppm含まれる非常に細粒（～100Å）なダイヤモンド内部に保持されていることが知られている．Qガスが衝撃により選択的に脱ガスされるのは，Qフェイズが衝撃に弱く衝撃圧によりその構造を変化させQガスを放出したためだと考えられる．しかしながら，HLガスを含むダイヤモンドは衝撃に強く，70GPaの衝撃圧に対しても変化せずHLガスを放出しなかったと考えられる．

　衝撃圧によりQガスが選択的に脱ガスされることで生じる具体的な希ガス組成の変化は（1）4/１32，2０/１32といった元素比の上昇，（2）124/132，136/132といった同位体比の上昇がある．これらはいずれも衝撃により，HLガスが始源隕石中にとどまりQガスが選択的に脱ガスされるという脱ガス機構に起因している．それに対し，36/１32，84/132といった元素比は衝撃を与えても変化しない．このことは，Qガスが脱ガスされる際に元素分別を起こさなかったということを意味している．始源隕石中の希ガスを分析する際に，段階加熱法という試料を段階的に熱し，それぞれの温度で放出される希ガス組成を計測するといった方法が一般的に用いられているが，それによるとQガスは摂氏1200度程度で大部分が放出されるのに対し，HLガスはQガスより低温の摂氏800-1000度で放出されることがわかっている．このことは，熱に対してはQフェイズの方が，HLガスを含むダイヤモンドよりも強いということを示唆している．これは，STATICな熱変成では，QガスよりもHLガスの方が失われやすいということを意味する．しかしながら，衝撃に対しては逆で，Qフェイズの方がHLガスを含むダイヤモンドよりも弱いということが，本研究により明らかになった．結論としては，熱変成という長

時間での脱ガス現象と，衝撃という短時間での脱ガス現象は，どちらも太陽系初期の小天体上で起こっていたことが知られているが，その際の希ガスの脱ガス過程は異なり，熱変成では軽い希ガス（HLガス〉が，また，衝撃では重い希ガス（Qガス）が選択的に失われる可能性が高いということである.

これらの結果は，1997年3月にアメリカ合衆国ヒューストンで行われる月惑星会議で発表されることになっている（添付資料参照）.

添付資料：

SHOCK EFFECTS ON PHASE Q AND HL DIAMONDS INFERRED FROM EXPERIMENTAL SHOCK LOADING ON ALLENDE METEORITE.

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Impact events on the planetary bodies in the early solar system is a fundamental process that affected on physical and chemical properties of the primitive chondritic materials. Volatile elements such as H2O, CO2 and radiogenic Ar are known to be lost by impacts from chondritic meteorites [1, 2] and volatile-bearing minerals [e.g., 3]. Experimental studies concerning shock effects on noble-gas abundance have been done mostly on the radiogenic Ar [e.g., 2, 4], but little is known about shock effects on primordial noble gases. In the early stage of the solar system formation, predominant noble gases in the planetary bodies were the primordial ones that had been incorporated during formation of these bodies. Major components of the primordial noble gases are Q-gas and HL-gas. The former dominates primordial Ar, Kr, and Xe, and the latter comprises most of primordial He and Ne [5]. The two types of primordial noble gases are sited in different carrier phases; ill-identified carbonaceous matter called phase Q for Q-gas [e.g., 6] and tiny diamonds of interstellar origin for HL-gas [e.g., 7]. These two carrier phases are found to be distributed in any type of primitive chondritic meteorites [8]. Therefore, shock effects on phase Q and HL diamonds are essential issues to be addressed, in order to elucidate effects of impacts on noble gas abundance in the primitive planetary bodies.

A series of shock-recovery experiments were performed on the Allende CV3 chondrite, which is rich in primordial noble gases. with peak pressures of 30, 47, and 70 GPa using a single stage propellant gun. To avoid adsorption and implantation of atmospheric noble gases, Allende sample was preheated to ¯180 ℃ for 4 hours in the gun chamber, ambient air was replaced by N2 gas during cool down the sample, and the sample was evacuated down to 1¯ 4 x 10-2 torr through a vent in a stainless sample holder. The recovered samples were examined using an electron microprobe and analyzed for noble gas composition using a noble gas mass spectrometer by a stepped heating technique with eight temperature steps, 350, 450, 600, 800, 1000, 1250, 1550, 1850 ℃.

Petrological observations: Cross sections of the Allende samples shocked at 30 and 47 GPa exhibit a high degree of porosity reduction of matrix and flattening of chondrules, which is consistent with results of experimental shock-loading on Allende in a previous study [9]. Fine-grained olivine, low-Ca pyroxene, Fe-Ni metal and sulfide in the matrix of the 30 GPa product appear not to be melted, whereas those in the 47 GPa product are melted in some portion, where metal and sulfide grains became rounded. An Allende sample shocked to 70 GPa shows a drastic petrological modification: matrix is totally melted, numerous small gas bubbles with diameters from 1 to 30 mm are generated, and chondrules are partially melted and disaggregated. The melt of matrix containing high densities of the bubbles intrudes into cracks in a metallic sample holder.

Noble gas analysis: All noble gases (He-Xe) were measured in the three shock-loaded products and a natural Allende sample for reference. Measured noble gases were separated into primordial, radiogenic, and cosmogenic components using reported isotopic ratios of these three components [e.g., 10]. Moreover, primordial 20Ne and 132Xe amounts were separated into Q- and HL-gases, i.e., (20Ne)Q vs. (20Ne)HL, and (132Xe)Q vs. (132 Xe)HL using Xe-Q, Xe-HL isotopic ratios [6, 11] and a (20Ne/132Xe)Q elemental ratio [11]. Results of the stepped heating analyses show that noble gases in

350 ℃ fractions in all four samples were dominated by absorbed or implanted air except for He. thus Ne-Xe in the 350 ℃ fractions are excluded from total amounts of released noble gases.

Concentration of heavy primordial noble gases such as 36Ar, 84Kr, and 132Xe decreases in the order of unshocked Allende, 30, 47, and 70 GPa samples: (132Xe)Q concentrations are 9.4, 6.9, 5.9, and 2.4 x 10 -10 cc STP/ g, respectively. This indicates that phase Q lost up to 75% noble gases due to experimental shock-loading. Release patterns of (132Xe)Q of unshocked Allende, 30, 47, and 70 GPa samples are basically similar, although gas-amounts of each temperature step are reduced, suggesting heterogeneous shock effects. Phase Q which suffered heavier shock effects lost all noble gases including gases in highly retentive sites, while that suffered lesser degree of shock effects retained most noble gases. A slight difference in the release patterns is seen between unshocked and shocked (30 and 47 GPa) samples. The latter shows a small peak at an 800℃ temperature step. This fact might indicate that minor parts of phase Q change gas-retentivity by impacts. Similar features are also observed in analyses of both experimentally shocked Allende at 23 GPa [12] and the Leoville CV3 chondrite [13] which experienced shock pressure ¯ 20 GPa in space [14].

Unlike phase Q, HL diamonds did not lose noble gases by shock loading. Amounts of HL-gases such as (20Ne)HL and (132Xe)HL were relatively constant in the unshocked and shocked samples: (20Ne)HL concentrations are 2.2, 2.9, 2.5. 2.1 x 10-10 ccSTP/ g for unshocked, 30, 47, and 70 GPa samples. Release patterns of (20Ne)HL from all the four samples are also similar. Thus, HL diamonds appear to keep concentration and gas-retentivity of noble gases, even after 70 GPa shock. Large amounts of HL-gas were extracted in 800-1000 ℃ fractions in the stepwise heating experiments, whereas Q-gas has a largest extraction peak at 1250 ℃, indicating that HL diamonds are weaker to thermal effects than phase Q. However. in contrast, HL diamonds are stronger against shock effects than phase Q. The reason why HL-gas was not lost by a strong shock compression is uncertain, but HL-gas is likely to be rigidly trapped in the crystal structure of diamonds. As a results of preferential loss of Q-gas from shocked samples, remained noble gases tend to have higher ratios of HL/Q, resulting in a change of isotopic ratios especially those of light and heavy Xe isotopes.

Radiogenic 40Ar seems to be unaffected by 30 and 47 GPa shock loading. Two large extraction peaks at 800 and 1250 ℃, which observed in the analysis of unshocked Allende sample, are observed in analyses of both 30 and 47 GPa samples. But, the 70 GPa sample shows apparent decrease of released-Ar amounts in low temperature fractions, 450-800 ℃. Coupled with the results of petrological observations, the 40Ar loss from the 70 GPa sample is due to diffusive loss from matrix material that was totally melted by the effects of 70 GPa impact. But, the 1250 ℃ peak was still observed in the 70 GPa-sample analysis. which is consistent with the petrological observation that most chondrules in the 70 GPa sample suffer only partial melting. The same tendency was observed in the extraction of cosmogenic noble gases: concentrations of cosmogenic 21Ne and 38Ar in the unshocked Allende, 30, and 47 GPa samples were relatively constant but those in the 70 GPa sample decrease by approximately 50% in total amounts. The 21Ne and 38Ar loss is observed especially in the low temperature fractions, indicating diffusive loss from the matrix material, like the case of radiogenic 40Ar.

Acknowledgments : The authors appreciate the technical support of Messrs. G. Haynes and W. Davidson in the shock experiments at NASA JSC.

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