THE ORIGIN OF UREILITES: A NOBLE-GAS PERSPECTIVE. Sachiko Amari[1,2], [1]McDonnell Center for the Space Sciences & Physics Department, Washington University, St. Louis, Missouri, 63130, USA (sa@physics.wustl.edu), [2]Geochemical Research Center, Graduate School of Science, The University of Tokyo, Hongo, Tokyo 113-0033, Japan.

Introduction: Ureilites comprise the second largest group of achondrites after HED meteorites. The main group ureilites are coarse-grained ultramafic rocks consisting mainly of olivine and pyroxenes and are thought to represent the mantle of a partially melted, carbon-rich asteroid [e.g., 1, 2]. Bulk C contents of ureilites range from ~0.2 to 8.5% [3].

Ureilites show highly fractionated igneous features, and at the same time show primitive characteristics. They include the O isotopic values that plot along the Carbonaceous Chondrite Anhydrous Mineral (CCAM) line [4, 5] and the presence of abundant noble gases that are very similar to those in primitive chondrites [e.g., 6].

The efforts to decipher the formation and evolution of the ureilite parent body (UPB) and ureilites have been mainly focused on silicate portions of ureilites. The presence of the noble gases has largely been overlooked in these efforts and in formation scenarios. Here we propose a scenario on how the UPB and ureilites evolved, taking the presence of abundant noble gases into account.

Discussion: Noble gases in ureilites are mostly carried by diamonds [7]. Two origins of ureilite diamonds have been proposed. One is that they were transformed from graphite by shock [8] and the other is that they were produced by chemical vapor deposition (CVD) [9, 10].

Simulation experiments of diamond synthesis and noble gas trapping. Matsuda and his collaborators carried out several series of simulation experiments to decipher the origin of diamonds and noble gases in ureilites.

Matsuda et al. [10] synthesized diamonds in the H_2 atmosphere with a small amount of CH_4 and noble gases using a microwave to ionize the gas, and showed that CVD diamonds can reproduce the noble gas abundance pattern, which is highly fractionated in favor of the heavy noble gases, and high noble gas concentrations in ureilites. They concluded that ionization of noble gases and subsequent ion implantation was the process by which the CVD diamonds acquired the noble gases. Depending on the conditions, graphite and amorphous carbon also formed during the CVD process [9, 11]. Those CVD products must have contained noble gas by ion implantation.

Shock experiments to transform graphite into diamond indicated that shock-produced (SP) diamonds retained the noble gases that were originally in the graphite in an open container [12]. It appears that 25 GPa is the critical shock pressure, under which diamonds cannot be produced [12].

CVD process in the solar nebula. Protoplanetary disks are subjected to UV radiation from their parent T Tauri stars and are penetrated by X-rays and excess UV photons. Model calculations of ionization fractions in a protoplanetary disk [13] show that the fractional abundance of electron (relative to total H nuclei density) can go up to 10^{-1} at the surface of a protoplanetary disk and down to 10^{-12} close to the mid-plane of the disk, indicating that there were ionized regions in the solar nebula.

Another essential ingredient, CH_4, is produced from the following reaction [14].

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$

Thermodynamic calculations show that CH_4 formation started at $800 - 1400$ K at 10^{-5} to 10^{-1} atm at the solar composition [15]. Therefore, it is reasonable to assume that there were regions where CVD took place and the CVD products with noble gases could be synthesized in the early solar nebula. A planetesimal that contained the CVD products might have become a impactor that caused the catastrophic breakup of the UPB.

Noble gases in ureilites and primitive chondrites. Despite the igneous features, the noble gas contents of ureilites are as high as those of primitive chondrites. Furthermore, the elemental and isotopic patterns from both types of meteorites are strikingly similar to each other. Primitive chondrites contain another, a highly anomalous Xe component called Xe-HL, which is enriched in both *h*eavy isotopes (134 and 136) and *l*ight isotopes (124 and 126), and presolar diamonds are the carrier of Xe-HL. The abundance of those presolar diamonds decreases with increasing petrologic type [16]. It was interpreted as evidence that these noble gas carriers were degassed during thermal metamorphism. Presolar diamonds are absent in Julesburg (L3.7), consistent with this interpretation [16]. It is estimated that peak temperatures for type $3.7 - 3.8$ ordinary chondrites were 525–600°C [17]. From the $(^{26}Al/^{27}Al)_0$ ratios of chondrules from type > 3.5 ordinary chondrites and CAIs from type > 3.8 ordinary chondrites, assuming that these low ratios reflect parent body metamorphism, Huss et al. [18] concluded that high temperatures lasted until at least 5 Ma after CAI. Therefore,

presolar diamonds lost their noble gases due to thermal metamorphism at 600°C for a few million years.

The UPB experienced much higher temperatures than the metamorphosed chondrites. Equilibrium temperatures estimated from the silicate mineral assemblages of ureilites are ~1150 – 1300°C [19, 20]. From ^{26}Al-based thermal modeling, the UPB accreted 0.5 – 0.6 Ma after CAI, with differentiation starting approximately 1 Ma after CAI [21, 22]. The catastrophic impact disruption of the UPB, which occurred while ureilites were still at ~1000-1050°C [1, 23], took place ~5 Ma after CAI [24]. Therefore, the UPB experienced much higher temperatures than ordinary chondrites for several million years. If presolar diamonds in chondrites lost their noble gases during the thermal metamorphism, then diamonds in ureilites certainly must have lost their noble gases during the high temperature igneous processes that their host experienced. Therefore, the noble gases in ureilites must have been added at a later stage of ureilite evolution, i.e., after the igneous processing. Furthermore, at the time that noble gases were added, igneous activity must have terminated. Otherwise, the noble gases would have been quickly lost. We propose that the presence of noble gases in ureilites is best explained if they were added to ureilitic material during the catastrophic disruption of the UPB from a gas-rich impactor.

Catastrophic breakup of the UPB. The Grand Tack dynamical model [25] describes processes that took place during the first million years of the solar system history, modelling the movement of Jupiter, Saturn and asteroids. The asteroid belt first was fully emptied when the giant planets migrated inward [25, 26]. When they finally migrated outward toward their current locations, it was repopulated by planetesimals. The inner asteroid belt was repopulated mainly by those that were originally inside the orbit on which Jupiter formed, possibly corresponding present-day S-type asteroids. On the other hand, the outer part of the asteroid belt was repopulated mainly by those that originated between and beyond the orbits of the giant planets, i.e., present-day C-type and other primitive asteroids. The collision of the UPB and a noble-gas-rich impactor could have been one of such incidents. The impactor could be one of the C-type asteroid moving toward the asteroid belt and the UPB could be one of the S-type asteroid also coming back the asteroid belt [26].

It is estimated that the catastrophic disruption of the UPB at ~ 5 Ma after CAI [22, 23]. Those migrations of the giant planets and planetesimals took place when the solar nebula was still gas-rich because the migration of the giant planets during the Grand Tack is caused by interactions with the gaseous disk [26]. If the solar nebula lasted for 4 – 5 Ma and the dissipation of the gaseous nebula marked the end of the onward

movement of the giant planets, it is consistent to the timescale that was recorded in ureilites [24, 27].

When the UPB was catastrophically disrupted, the high temperature igneous conditions in the UPB were suddenly terminated. Cooling rates of 1-20°/hr, accompanied by a drop in pressure through the range ~1100-700°C, are recorded in ureilite olivine [1, 23]. Whether gas-rich CVD products retained their noble gases depended on the peak temperatures they experienced during the impact and reassembly. Goodrich and Desch [28] estimated that UDB assembly temperatures were 1100 ± 100 °C when they formed just after the breakup. If this is an average temperature, most of the gas-rich CVD diamonds could retain their noble gases, but most of the graphite and amorphous carbon would have lost their noble gases. Therefore, it is expected that noble-gas-rich diamonds are mainly CVD diamonds. If the shock pressure above 25GPa, there might have been the formation of gas-rich SP diamonds. If the conditions were met, gas-rich graphite [29] and amorphous carbon [30] from CVD could also retain noble gases.

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