様　式　Ｆ－１９－２

科研費
KAKENHI

科学研究費助成事業　　研究成果報告書

令和　　元 年　　６ 月 １４ 日現在

機関番号：１２６０８
研究種目：国際共同研究加速基金（国際共同研究強化）
研究期間：2018～2018
課題番号：１７ＫＫ００８９
研究課題名（和文）When could Earth have developed a biosphere?

研究課題名（英文）When could Earth have developed a biosphere?

研究代表者
ブラサー　ラモン（Brasser, Ramon）

東京工業大学・地球生命研究所・特任准教授

研究者番号：３０７４７１４２

交付決定額（研究期間全体）：（直接経費）　　4,000,000円
渡航期間：　　６ヶ月

研究成果の概要（和文）：本研究では、4.4-4.3十億年前(Ga)に地球上に生命が誕生したと示した。約4.5 Gaの月形成により地球が溶融し地球上の生命が絶滅した。この破壊イベントに続く4.48 Gaのレイトベニヤイベントで地球は月サイズの天体と衝突し、地球地殻の大部分が再溶融して地殻のウラン・鉛年代をリセットした。衝突した天体の金属コアが雹として地球に降り注ぎ、水と反応して一時的に水素大気を形成し、RNAベースまたはその他の生命体を形成する還元的な環境が生まれた。水素大気は約4.2 Ga までに消滅したため、生命は約4.3 Ga に誕生したと考えられる。酸素同位体比によると、4.3 Ga には地球上に水圏があった。

研究成果の学術的意義や社会的意義
全ての生命活動は水を必要とする。約43億年前、地球には安定的な海があった。それ以前は、表面が溶けており、生命が存在するには暑すぎる環境だった。43億年前、今日のように地球が温暖になり、生命が誕生した可能性がある。44.8億年前に地球へ大きな衝突があったことにより、水素大気が形成され、海洋の化学物質と反応することでRNAベースの生命が誕生した。

研究成果の概要（英文）：We have established when life could have begun on the Earth. Our best estimate is between 4.4 and 4.3 billion years ago (Ga). We have determined the following: Approximately 4.5 Ga the Moon formed, which melted the Earth and thus would destroy any life that was present. This catastrophic event was followed by the late veneer event at 4.48 Ga, wherein the Earth was struck by a moon-sized object. This impact melted a large portion of Earth's crust again and reset some of the U-Pb ages in the crust. The metallic core of this object was torn apart in the impact and subsequently rained onto Earth as a metallic hail. This hail reacted with water to form a temporary hydrogen atmosphere. This atmosphere created a reducing environment to form the chemical building blocks for RNA-based life, or another form of life. The temporary hydrogen atmosphere was gone by about 4.2 Ga, so that life must have begun around 4.3 Ga. Oxygen isotopes on Earth shod there was a hydrosphere at 4.3 Ga.

研究分野： Planetary science

キーワード： origin of life　large impact　crater chronology　rna chemistry

１．研究開始当初の背景

Earth is the only planet in the solar system that has life. Yet very little is understood about how life formed on Earth, and how it evolved from primitive singl-celled organisms to the fully-fledged biosphere that we have today.

In order to understand how life came to exist on Earth we need to combine many aspects of research. We need to combine planetary science, geology and geochronology with pre-biotic chemistry and biology because life is an integral part of the planet. Without a planet there is no life. As such, the search for the origin of life begins with a study of planetary-scale processes and how the planet evolves as a whole while it is still young and geologically active.

In this study we have focused on a particular aspect of the origins of life, namely what was the early evolution of the Earth when subjected to impacts from leftover debris from terrestrial planet formation.

After the terrestrial planets (Mercury, Venus, Earth and Mars) formed, they leave behind a lot of material in the form of small planetesimals. These stray objects are flying around the inner solar system on eccentric and inclined orbits and they will have frequent close encounters with the terrestrial planets. Most of these objects will eventually collide with a terrestrial planet or with the Sun, with a few other objects flung out of the solar system through interaction with Jupiter. These planetesimals, plus comets arriving from the outer solar system, will cause major discomfort for life to develop.

We ask ourselves this: How did the high frequency of impacts of these stray asteroids with the young Earth affect its ability to create a biosphere?

Such impacts (locally) melt the Earth's crust. This melting causes extremely high local temperatures that are far hotter than what life can withstand. As such, a high impact flux will cause global scale crustal melting and no life can exist, yet there will come a point in time when the flux is low enough that life can begin to form. When did this happen?

２．研究の目的

Our main research objective was to constrain the likely timing for the origins of life on Earth. To do so we were interested in constraining the tempo and intensity of the impact bombardment onto the early Earth from leftover planetesimals from terrestrial planet formation. We have attempted to understand how much of Earth's crust was molten after the Moon-forming impact at any time, how much of Earth's crust was completely reset during the first billion years of bombardment, and when the intensity of impact bombardment was low enough that almost now crustal melting occurred and life could form a suitable niche to thrive. During this work, we discovered that we also need to pinpoint the timing of the arrival of the comets, because the expectation is that they will cause a short but intense burst of bombardment that could frustrate life, but not eliminate it (Abramov & Mojzsis, 2009). As such, we began by investigating when the comets arrived. Their timing is directly llinked to the timing of giant planet migration. A schematic of this is given in Figure 1.

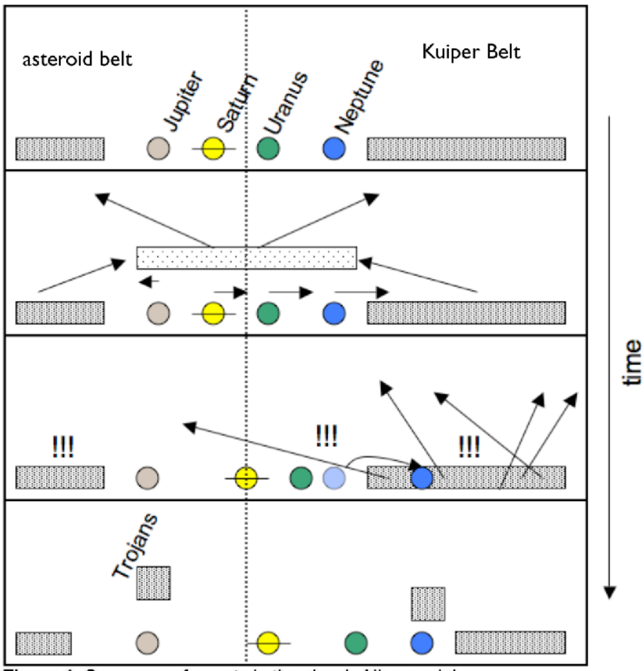

Figure 1. Sequence of events in the classic Nice model

３．研究の方法

Our research primarily consisted of running numerical simulations of the evolution of the solar system, and the effects of bombardment on the terrestrial crust.

First, we ran a series of numerical dynamical simulations of the solar system after the terrestrial planets had formed. We included planetesimals that were taken from a database of terrestrial planet formation simulations in the PI's possession. From that database we took a snapshot at 60 Myr of the orbital distribution of the planetesimals. We then continued to simulate these planetesimals with the current terrestrial planets on their current orbits. The software that we used is the SWIFT RMVS3 package (Levison & Duncan, 1994) that the PI is very familiar with. The code recorded the impacts onto the terrestrial planets. We ran 32 simulations with 1074 test particles each for 500 Myr. These simulations took about 2 months each.

Next we ran 32 simulations with 512 test particles each from the purported E-belt (Bottke et al., 2012) which can also cause an intense bombardment onto the early Earth. Once again we used the SWIFT RMVS3 package and all the solar system's planets were on their current orbits. The initial conditions for the test particles came from Bottke et al. (2012). The simulations took about 5 months.

A third series of simulations involved constraining the role of comets on the terrestrial bombardment. The role of comets is widely disputed amongst the experts, but we felt obliged to add them in. To do so we modelled the comets arriving from the outer solar system during an epoch of giant planet migration. We kept track of comets that came closer than 1.7 au to the Sun and we then subsequently remodelled those comets passing by the terrestrial planets (see Mojzsis et al., 2019 for details).

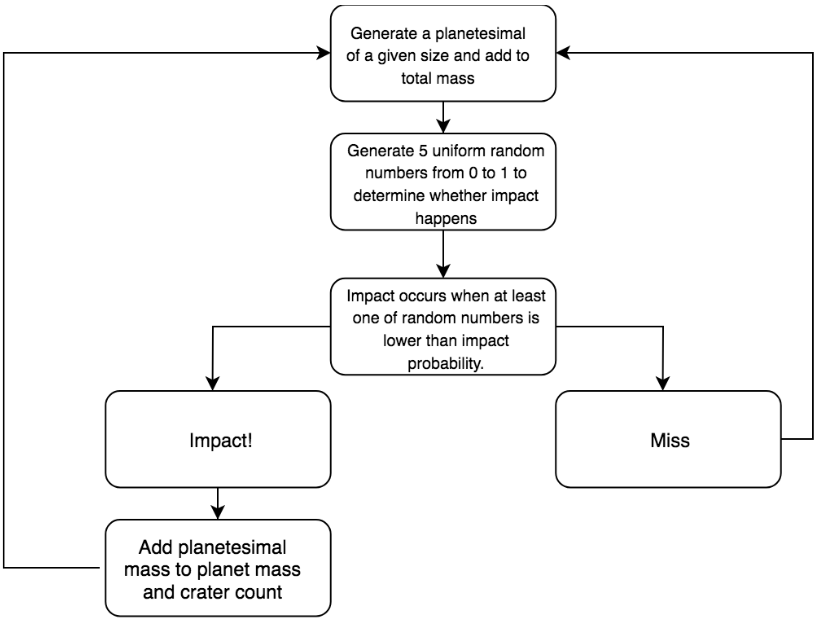

Figure 2: Chart of the Monte Carlo method for impacts onto the terrestrial planets.

From all of the simulations we computed the impact probability with the planets. These impact probabilities formed the input for a Monte Carlo code to compute the total number of impacts with the Earth (and the other terrestrial planets), and the total mass that was accreted by the Earth. Figure 2 shows a schematic flow chart of the Monte Carlo code. The input is the size-frequency distribution of the planetesimals. The output is the amount of mass accreted onto each planet and the total mass in planetesimals. We kept track of the number of craters on Mars and the Moon to compare with their crater chronology histories because they will serve as a general indicator of the validity of the model of terrestrial planet formation that we chose to use. We ran the code for the comets, the leftover planetesimals and the E-belt. The simulation was stopped once the Moon had accreted 0.025 wt% of its total mass (Day & Walker, 2015; Touboul et al., 2015) or when the total mass the E-belt exceeded 4×10^{-4} M_E. in See Brasser et al. (2019) for further details.

Last, we compiled a database of radiogenic reset ages of asteroidal mateorites to determine when the giant planets could have migrated, and thus when the comets arrived (Mojzsis et al., 2019).

4． 研究成果

From the reset ages of radiogenic meteorites, we conclude that the giant planets must have begun their migration at 4.48 Ga (Mojzsis et al., 2019) . The ages depicted in Figure 3 show that the minerals that are the most resistant to impacts have no reset ages younger than 4.45 Ga. As such, we concluded that the giant planets must have begun their migration

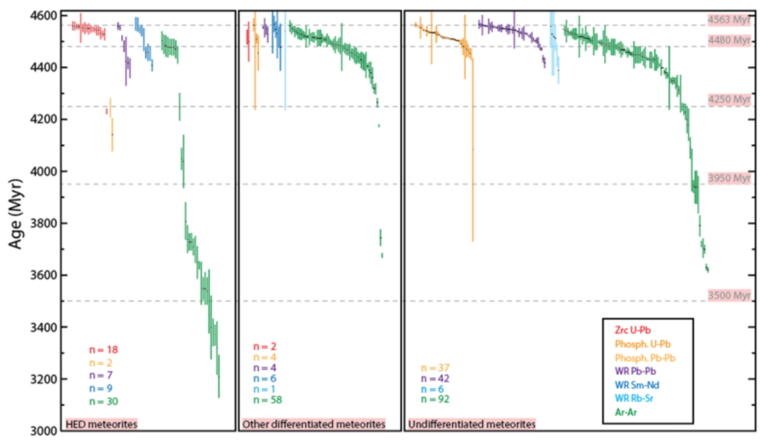

Figure 3. Asteroid reset ages (Mojzsis et al., 2019).

before 4.45 Ga. The dynamical simulations of the evolution of the comets showed that their impact spike lasted no longer than about 30 Myr. Since lunar hydrogen and xenon isotopes indicate it could have seen the cometary bombardment, we opine that the giant planets begun their migration between 4.48 and 4.45 billion years ago. The impacts on the Earth were able to melt a considerable portion of the crust. Figure 4 shows the evolution of the amount of crustal melting that the Earth endured (Mojzsis et al., 2019). At 4480 Ma the bombardment is extremely intense, but by 4000 Ma the bombardment has decreased by several orders of magnitude. The instantaneous amount of crust that is molten at any given time peaks around 4450 Ma and reaches 25%; the total crust that is completely molten over the first 500 Myr is nearly 80%, while >100% of the crust is completely reworked (either molten or reset or eroded). The total volume of crust where living organisms could thrive was still many millions of cubic kilometers, so that even though the Earth was pummelled by material from outer space, it was still able to create niches were life could have endured.

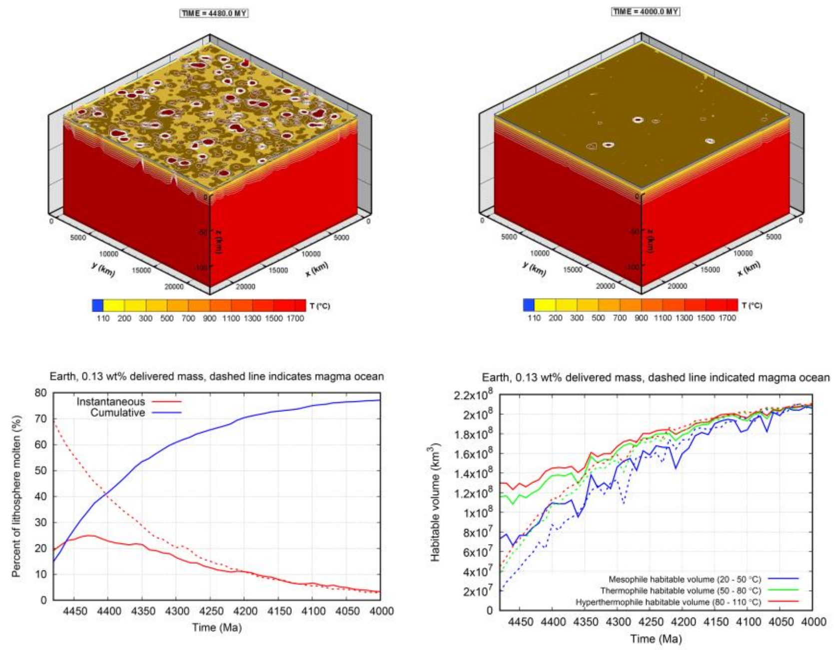

Figure 4. Bombardment intensity, amount of lithosphere molten and the volume of crust that can be inhabited.

The impact cratering chronologies for Mars and the Moon that we obtained from the dynamical and Monte Carlo simulations are shown in Figure 5. With nominal leftover and E-belt mass we can reproduce the lunar and martian crater chronologies (Brasser et al., 2019). The comets arrive very early and are gone in ~30 Myr. These bodies will not leave any cratering on the Moon and Mars because the expectation is that the crusts of these bodies were molten at that time (evidence for Mars comes from zircons with ages of 4.475 Ga; Bouvier et al., 2018). The decline of the leftover planetesimals is also extremely rapid. As such, we opine that the cratering on these bodies is caused almost compeltely by the E-belt reservoir. We opine that this indicates that the E-belt reservoir actually existed because it is the only reservoir whose decline is slow enough to match the calibrated lunar and martian crater chronologies of Werner (2019). We discussed these results with colleagues who perform pre-biotic RNA chemistry and they conclude that due to the large temporary hydrogen atmosphere created by the late veneer impact (Genda et al., 2017), life could have arisen on Earth near 4.35 Ga.

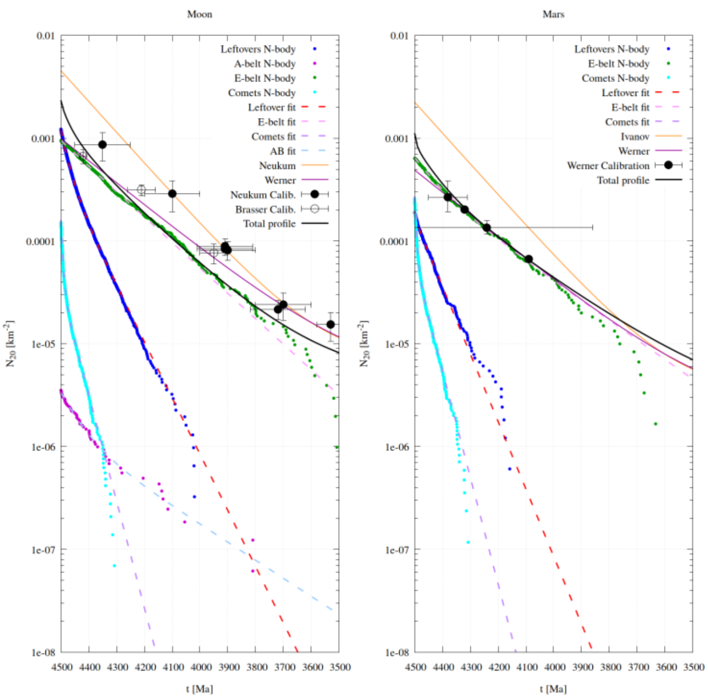

Figure 5. Lunar and martian crater chronologies from crater counts (Werner, Neukum) and simulations.

５．主な発表論文等

〔雑誌論文〕（計　２　件） **(All articles are peer reviewed)**
1. S. J. Mojzsis, R. Brasser, N. M. Kelly, O. Abramov and S. C. Werner. Onset of Giant Planet Migration before 4480 Million Years Ago. *The Astronomical Journal*, in review (2019).
2. R. Brasser, S. C. Werner and S. J. Mojzsis. Impact bombardment chronology of the terrestrial planets from 4.5 Ga to 3.5 Ga. *Icarus*, in review (2019).

〔学会発表〕（計　１　件）
1. Late accretion and the Origin of Life on Earth. Origins of Life Workshop. Atlanta, GA; USA. October 2018. (Presentation by Ramon Brasser).

〔図書〕（計　0　件）

○出願状況（計　0　件）

名称
発明者
権利者
種類
番号
出願年月日
国内外の別

○取得状況（計　0　件）

名称
発明者
権利者
種類
番号
取得年月日
国内外の別

〔その他〕
ホームページ等
Origins of Life Workshop: http://templetonorigins.ffame.org/OriginsConference2018.aspx

６．研究組織

研究協力者

〔主たる渡航先の主たる海外共同研究者〕

研究協力者氏名：モジスス スティーベン

ローマ字氏名：Stephen Mojzsis

所属研究機関名：University of Colorado Boulder

部局名：Geological Sciences

職名：Professor

〔その他の研究協力者〕
研究協力者氏名：
ローマ字氏名：