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研究課題名（和文）高精度長時間シミュレーションによる初期地球への小天体衝突率の推定

研究課題名（英文）Planetary bombardment in the first billion years of the solar system

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

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研究成果の概要（和文）：本研究では太陽系形成および発達の最初の10億年の期間での地球型惑星への隕石衝突の強度を計算した。計算には地球型惑星形成の動的N体シミュレーション、その後の動的発達および衝撃のモンテカルロ・シミュレーションを組み合わせた。地球と火星のマントル内の強親鉄性元素の過剰と火星物質中の同位元素の変動から隕石衝突の強度が限定されると考えた。結論として41億年あるいは39.5億年前に後期隕石爆撃はなく隕石衝突は44億年前以降に次第に減衰し、地球は44億年前以降に生物圏を形成するに至った。さらに、火星は、太陽から離れて小惑星帯の中で形成されこれが初期太陽系の発達において明確な境界となったという結論に達した。

研究成果の概要（英文）：We have calculated the intensity of bombardment onto the terrestrial planets within the first 1 Gyr of the formation and evolution of the solar system. We employed a combination of dynamical N-body simulations of terrestrial planet formation, their subsequent dynamical evolution and Monte Carlo impact simulations. We constrained the intensity of the bombardment against the abundance of highly-siderophile elements in the mantles of Earth and Mars, and isotopic variations in martian materials. We conclude that there was no late heavy bombardment at 4.1 Ga or 3.95 Ga, the bombardment was a monotonic decline from 4.4 Ga onwards and that the Earth was conducive to forming a biosphere from 4.4 Ga onwards. We further conclude that Mars formed far from the Sun, in the asteroid belt, which places severe limitations on the evolution of the early Solar System.

研究分野：Planetary science

キーワード：planetary bombardment

１．研究開始当初の背景

Hadean (pre-3900 Ma) terrains are the oldest and most heavily cratered on the Moon, Mercury and Mars, the latter two having crater densities comparable to the ancient (4400 Ma) highlands of the Moon. All three bodies underwent late accretion – after silicate reservoir separation – and were heavily bombarded during the first few hundred million years of the Solar System. Post-planet formation accretion (dubbed ‘late accretion’) has been suggested to follow either a ‘saw-tooth’ intensity profile with an uptick either at 4.1 Ga or 3.95 Ga, or a monotonic decay. Traditionally the peak bombardment was thought to occur at 3.95 Ga, and recently the start has been pushed to 4.1 Ga, the supposed age of Nectaris basin. However, recent evidence shows Nectaris is older, about 4.25Ga, casting its timing into doubt. From the resetting and fracture ages of zircons on the Moon, Mars and Vesta, the onset of the LHB has recently been determined to be earlier than 4.3 Ga, after which the bombardment declined monotonically. It lasted about 300 Myr on the Moon and about 2 Gyr on the Earth. The nature of this bombardment has profound implications for the environment on the early Earth and origins of life.

２．研究の目的

For this work we aimed to quantify the nature, composition, duration and intensity of the early bombardment of the inner solar system, as well as its time profile. We further sought to understand whether or not the purported Late Heavy Bombardment (LHB) occurred, and if so, when. The intensity of the bombardment needs to be constrained from dynamical simulations, whose initial conditions are taken from terrestrial planet formation simulations. Therefore we have also performed simultaneous studies of terrestrial planet formation and the effects of bombardment after the planets had formed, with a particular focus on Mars and Earth.

３．研究の方法

We have employed a mixture of dynamical N-body simulations of the formation of the terrestrial planets using the software package SyMBA in the framework of the Grand Tack model. We followed these simulations for a further 1 billion years to determine the time profile of late accretion onto the terrestrial planets. We have also performed Monte Carlo simulations of impacts on the terrestrial planets with a shallow size-frequency distribution to determine the nature of the late veneer (the earliest bombardment just after silicate separation). Last, we have used isotopic data from the literature to constrain the dynamical models and the nature of the bombardment. We were the first team to combine cosmochemical analysis with dynamical N-body simulations to constrain the formation of the terrestrial planets.

４．研究成果 Research Achievements

We have discovered that:

1) The late veneer on the Earth and Mars were caused by one large impact on each body (lunar-sized for Earth, Ceres-sized for Mars);
2) The amount of leftover material after terrestrial planet formation was much less than dynamical models predict, which requires further study of the models;
3) There was no LHB either at 4.1 Ga or 3.95 Ga. Instead, the bombardment followed a monotonic decay from 4.4 Ga onwards (Figure 1);

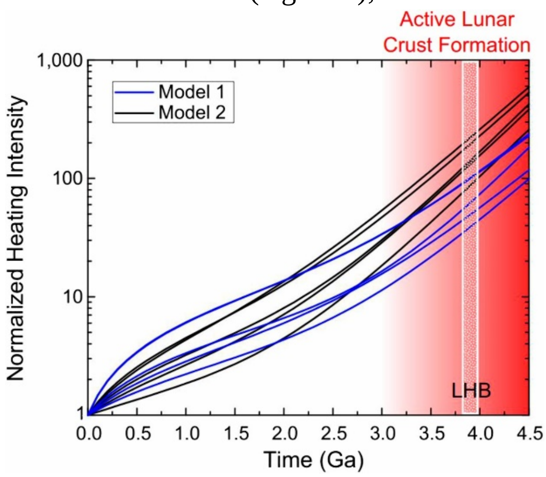

Figure 1. Updated lunar chronology curves from 40-39Ar dating. There is no sign of an uptick near 4.1 Ga or 3.95 Ga.

4) The Earth’s crust was no longer molten due to bombardment from 4.4 Ga onwards, paving the way for the planet to host a biosphere (Figure 2);

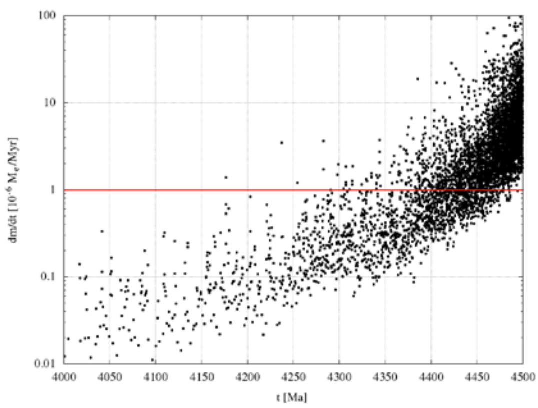

Figure 2. Bombardment intensity on Earth as a function of age. The crust can begin to form when the bombardment falls below the red line around 4.4 Ga.

5) The crusts of the Moon and Mars began to solidify at the same time, suggesting there is a common element in play that kept the crusts molten until then. The oldest zircon on the Moon has an age of 4417 Ma while that on Mars is 4428 Ma and on the Earth around 4404 Ma. The agreement of these ages cannot be a coincidence. We strongly believe that this is caused by bombardment-induced melting rather than indigenous volcanism.

6) We have reported that we think Mars formed in the asteroid belt rather than close to the Earth. In the framework of the Grand Tack model we think that its evolution was dominated by encounters with Jupiter before it parked near its current orbit (Figure 3);

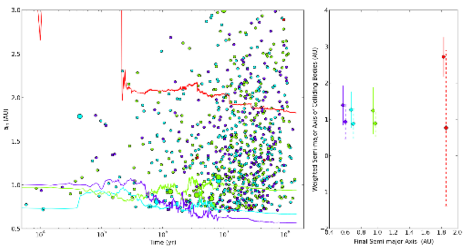

Figure 3. (*Left*) Semi-major axis evolution of a terrestrial planet formation simulation in the framework of the Grand Tack model. (*Right*) Feeding zones of the planets versus their final semi-major axes.

7) However, using better data from the terrestrial planet formation simulations that were performed for this study and a more accurate isotopic composition of Mars we found that we cannot constrain the history of Mars' accretion and formation location (Figure 4).

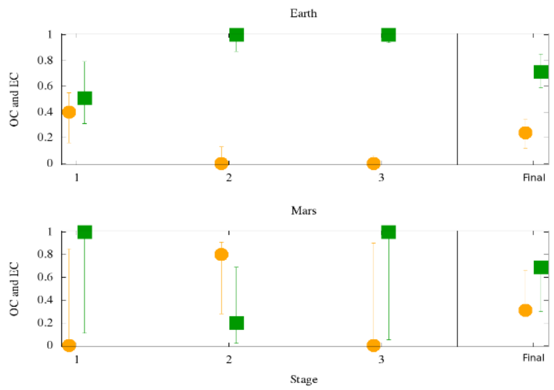

Figure 4. Fraction of enstatite (green) and ordinary (orange) chondrite that is accreted by the Earth (top) and Mars (bottom) during the first 60% (stage 1), next 39.2% (stage 2) and last 0.8% (stage 3) of their accretion. Final composition on the far right.

５．主な発表論文等（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計　８　件）

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late episode of giant planet migration (Asia Oceania Geosciences Society, 2017)
5)Brasser, R., Mojzsis, S., Matsumura, S., Ida, S., The Cool and Distant Formation of Mars (Asia Oceania Geosciences Society, 2017)
6)The Cool and Distant Formation of Mars (Division of Planetary Sciences of the American Astronomical Society, 2017)

〔図書〕（計　0　件）
〔産業財産権〕○出願状況（計　0　件）
名称：
発明者：
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名称：
発明者：
権利者：
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番号：
取得年月日：
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〔その他〕講義・アウトリーチ活動
Brasser, R., The Cool and Distant Formation of Mars (Collaborative for Research in Origins, 2017)

６．研究組織
(1)研究代表者：ブラサー ラモン（Ramon Brasser）
東京工業大学・地球生命研究所・特任准教授
研究者番号：30747142

(2)研究分担者：N/A（　　　）

研究者番号：

(3)連携研究者：N/A（　　　）

研究者番号：

(4)研究協力者：（　　　）