CHAPTER 1

Size distribution of asteroids and old terrestrial craters: Implications for asteroidal dynamics during LHB II.

Takashi Ito[1], Robert G. Strom[2], Renu Malhotra[2], Fumi Yoshida[1], and David A. Kring[2]

[1] *National Astronomical Observatory of Japan*
Osawa 2–21–1, Mitaka, Tokyo 181–8588, Japan
E-mail: tito@cc.nao.ac.jp

[2] *Lunar & Planetary Laboratory, The University of Arizona*
Tucson, AZ 85712–0092, USA

Recent progress in asteroid surveys has revealed the fine structures down to sub-km in diameter of the size-frequency distributions (SFD) of main belt asteroids (MBAs), as well as near-Earth asteroids (NEAs). These SFDs can be compared with the SFD of lunar and planetary crater projectiles. The SFD of the projectiles that created the oldest craters on the lunar highlands, which are considered a fossil of the Late Heavy Bombardment (LHB) impactors of ~ 4 Ga ago, shows a very good agreement with that of the current MBAs. This fact indicates that the LHB craters were created by the bombardment of ancient asteroids ejected from the main belt by a short-term, size-independent event, such as the radial movement of strong resonances due to the migration of giant jovian planets. On the other hand, the SFD of the projectiles that have created younger craters such as those on Mars is very different from that of the MBAs; instead, it is quite similar to the SFD of NEAs. This newer population of projectiles might be created by a long-term, size-dependent transportation mechanism of asteroids such as the Yarkovsky effect, which preferentially pushes smaller objects into strong resonances.

1. Introduction

At the dawn of Earth's history, there were intense and cataclysmic impact events, collectively called the Late Heavy Bombardment (hereafter we call LHB).[1,2] The most intense period of the LHB appears to have occurred

~ 3.9 Gyr ago, i.e. 500–600 million years after the formation of the Earth–Moon system.[3,4] Evidence of this event began to accumulate when Ar–Ar isotopic analyses of Apollo and Luna samples suggested that several impact basins on the nearside of the Moon had been produced 3.88 and 4.05 Ga. Additional analysis of Apollo samples indicated the U–Pb and Rb–Sr systems had been disturbed nearly uniformly at ~ 3.9 Ga, which was attributed to metamorphism of some portions of the lunar crust by a large number of collisions in a short time, less than 200 million years.

To better characterize the cause, mechanism, and extent of LHB, we can resort to the recent progress in extensive asteroid surveys that have revealed fine structures of the size-frequency distribution (SFD) of main belt asteroids (MBAs) and near-Earth asteroids (NEAs). These data can be compared with the SFD of the crater projectiles on the Moon and on other planets. In this paper we provide compelling new evidence that the source of the LHB impactors was the main asteroid belt, and that the dynamical mechanism that caused the LHB was unique in the history of the solar system and distinct from the processes producing the flux of objects that currently hit planetary surfaces.[5]

2. Crater SFDs

Throughout this manuscript, SFDs of craters and asteroids are expressed by the so-called R-plot, which expresses differential size-frequency distribution of crater/asteroid populations relative to D^{-3}, where D denotes diameter.[6] Since many populations of inner solar system small bodies and craters have differential SFDs (dN/dD) more or less proportional to D^{-3}, it is reasonable to normalize them by D^{-3} so that we can see their differences in detail. Also, R values of craters are generally divided by the surface area A where we count the number of craters in order to estimate the number density of craters; R is defined as $R \equiv (D^3/A) \times dN/dD$.

Expressing the SFD of lunar and planetary craters by R-plot, clearly we see two distinctive SFD populations (Fig. 1). The first crater population is what is typically observed on the oldest lunar highlands; LHB craters as old as $\sim$ 4Ga. This crater population is characterized by a wavy R curve as in Fig. 1(a), which is also seen on the oldest highlands on Mercury (Fig. 1(b)) as well as on Mars (Fig. 1(c)).

There is another crater population characterized by rather flat R patterns. These craters are younger than the LHB craters, and their number density is lower. In general, these craters have a wide variety of ages, in-

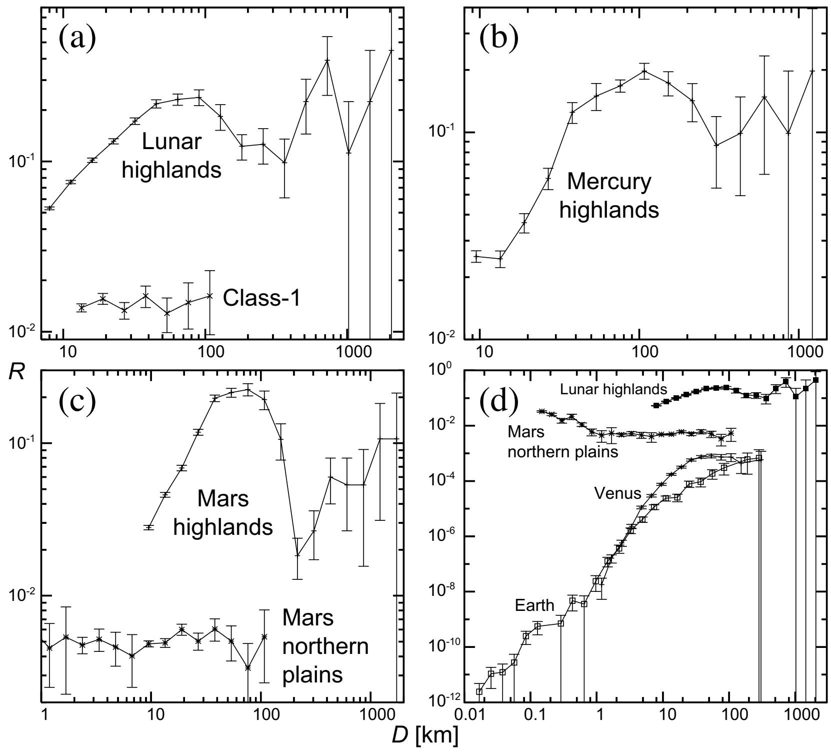

Fig. 1. *R*-plots of some crater SFDs. (a) Lunar highlands craters and lunar Class-1 craters. (b) Craters on the oldest mercurian highlands. (c) Craters on the oldest martian highlands and on young northern plains. (d) Craters on Venus and on the Earth, compared with the lunar highlands craters and young martian craters.

dicating they have been formed over a timespan as long as Gyr. A typical example of this population is seen on young and smooth northern martian hemisphere where there are a lot of relatively new craters. The R curve for these craters is almost flat, showing $R \propto D^{-3}$, as in the lower part of Fig. 1(c). Another example of this crater population is observed on the Moon as Class-1 craters with quite fresh morphology. These craters also have flat R curves with lower density than the old highland craters (lower left part of Fig. 1(a)). The crater records on Venus and the Earth have been severely obliterated and lost, or many of their projectiles have been screened out by the atmosphere, and we cannot use them to estimate their projectile sources (Fig. 1(d)).

The similarities amongst the wavy R curves of the oldest crater populations on the Moon, Mercury and Mars indicate that they were created by a single projectile population at the same age, probably during LHB with a short timescale. On the other hand, the younger crater populations characterized by the flat R curves having a variety of ages have presumably been created by a different projectile population with a different mechanism.

3. Asteroid SFDs

Chemical analyses of Apollo samples of impact melts point to a dominantly asteroid reservoir for LHB impactors, rather than to cometary objects.[4] Also, recent asteroid surveys with high resolution and large sky coverage such as Spacewatch, SDSS, or LINEAR have given us a significant degree of understanding of the SFD of MBAs as well as of NEAs. However, we cannot directly compare the SFD of asteroids with that of craters; it is necessary to convert crater SFD into that of projectiles (or the other way around). Procedures of this sort have already been established with the help of the scaling relationship between crater size and projectile size. In this paper, we assume the typical asteroidal impact velocity and asteroidal density as those of crater projectiles, and convert crater SFD into projectile SFD so that we can compare the SFD of crater projectiles with asteroid SFD. As for the SFD of MBAs, we use the results of three survey programs: Spacewatch,[7] SDSS,[8] and Subaru[9]. We rely on the results of the LINEAR program[10] for the SFD of NEAs. We used the so-called Pi scaling laws[11,12,13,14] to derive the projectile size from the crater size.

When we draw the asteroid SFDs on R-plot graphs, we immediately see their remarkable similarities to the SFD of crater projectiles. At first, the SFD of MBAs fits that of lunar LHB crater projectiles very well over wide diameter ranges (Fig. 2(a)(b)(c)). Second, the SFD of NEAs seems quite close to the SFD of the younger projectile population that has created craters on the younger martian plains (Fig. 2(d)). Thus, we obviously have two distinct SFD populations among current asteroids, not only among craters. These similarities should be more than just a coincidence, having firm physical/dynamical reasons.

4. Discussion

The fact that the ancient LHB projectiles had an SFD almost identical to that of the current MBAs could imply several things: First and foremost, there was a size-independent transport process for asteroids during the LHB period. If the LHB duration was as short as 50–200 Myr as previous

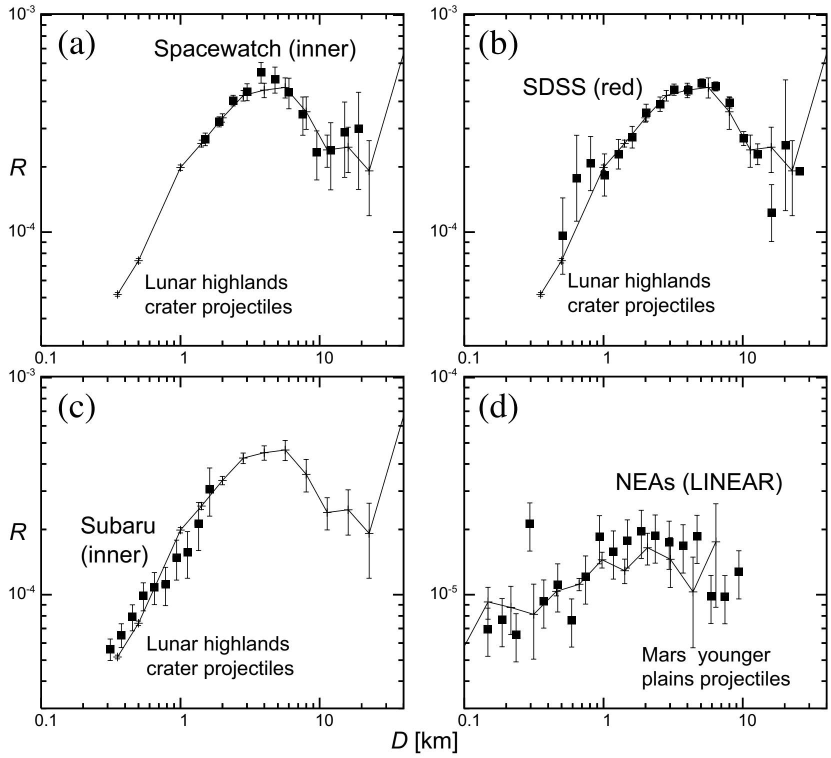

Fig. 2. Comparison between the SFDs of current asteroids (the symbol ■ with errorbars) and crater projectiles (solid lines with errorbars). (a)–(c) are for the oldest lunar highlands crater projectiles and the MBAs mainly in the inner belt surveyed by (a) Spacewatch,[7] (b) SDSS,[8] and (c) Subaru.[9] (d) is the comparison between the young martian crater projectiles and NEAs surveyed by the LINEAR project.[10] Note that the R range is different in (d) from other panels.

research suggests,[1] the timescale of the transport process must have been as short. Not so many dynamical mechanisms can make this drastic asteroid transport happen. A plausible candidate is the radial movement of strong resonances in the main belt caused by the migration of giant jovian planets.

Currently some ideas along this line are being proposed in terms of the late formation of Uranus and Neptune and their interaction with planetesimals.[15,16] LHB occurred too late to invoke a nebula gas dissipation as the cause of resonance sweeping, so the only alternative to provoke the resonance sweeping is that the giant planets migrated at that time due to interaction with a swarm of planetesimals. The planetesimal disk must be massive enough to make giant planets radially migrate, hence it should be a distant, massive planetesimal disk beyond the large planets. In addition, a mechanism is needed to produce a late start of giant planet migration around 4 Gyr ago. One possible theory invokes the change in the eccentricities of Jupiter and Saturn when they pass through a 1:2 mean motion resonance during their orbital migration[16] under the gravitational influence of a swarm of planetesimals. Such a resonance passage would have destabilized the planetesimal disk beyond the orbits of the large planets, causing a sudden massive delivery of cometary planetesimals to the inner solar system. In this scenario, the asteroid belt is also destabilized because of sweeping gravitational resonances; together, these cause a major spike in the intensity of cometary as well as asteroid impacts on the inner planets. The relative intensity of comets versus asteroids in the projectile population of the LHB is not well determined in currently published dynamical simulations. Because the impact signature of the crater record in the inner solar system is asteroidal, we conclude that either comets played a minor role or their impact record was erased by later-impacting asteroids.

Another important implication of our results comes from the fact that we have compared the SFD of 4 Gyr-old projectiles with that of the current MBAs, and found them strikingly similar. This could mean that there has been almost no collisional evolution in the main asteroid belt over the last $\sim$ 4 Gyr, ever since the LHB. This is seemingly weird, but recent numerical models of the collisional evolution of MBAs support this fact, [17,18] revealing the rather stationary SFD of MBAs. Therefore it is probably safe to regard the SFD of the current MBAs as a fossil of the LHB projectiles.

From the comparison between the SFDs of younger crater projectiles and the current NEAs, it seems that NEAs have been the impacting source of the newer craters since LHB ceased. Although most NEAs are considered to have originated in MBAs from a dynamical point of view,[19] we have a greater number of smaller objects among the NEA population than the MBA population, judging from the slope difference between Fig. 2(a)(b)(c) and Fig. 2(d). This evidence, in addition to the wide variety of ages of the young crater population, leads us to the conclusion that there has been a size-dependent, long-term transport process that conveys MBAs (preferentially smaller ones) to the inner solar system. A plausible candidate for this kind of mechanism is the Yarkovsky effect, a (generally slow) dynamical effect caused by the thermal time lag of asteroids when they absorb and re-emit solar radiation. Since the Yarkovsky effect works much more effectively on smaller asteroids, it is perfectly eligible to selectively transport small asteroids from the main belt to the terrestrial planet region over a long timespan.

Acknowledgments

The authors have greatly benefited from the electronic version of asteroid SFD data provided by Željko Ivezić and Joseph Scott Stuart. Two anonymous referees suggested directions which bettered the quality of this paper. Detailed and constructive review by Yolande McLean has considerably improved the English presentation of this paper. This study is supported by the Grant-in-Aid of the Ministry of Education of Japan (16740259/2004–2005). F.Y. acknowledges financial support from the Sumitomo Foundation for the research funding (030755/2003–2004).

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