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Towards understanding the dynamical evolution of asteroid 25143 Itokawa: constraints from sample analysis

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Abstract

The data from the analysis of samples returned by Hayabusa from asteroid 25143 Itokawa are used to constrain the preaccretion history, the geological activity that occurred after accretion, and the dynamical history of the asteroid from the main belt to near-Earth space. We synthesize existing data to pose hypotheses to be tested by dynamical modeling and the analyses of future samples returned by Hayabusa 2 and OSIRIS-REx. Specifically, we argue that the Yarkosky-O'Keefe-Radzievskii-Paddack (YORP) effect may be responsible for producing geologically high-energy environments on Itokawa and other asteroids that process regolith and essentially affect regolith gardening.

Keywords: Asteroids; Hayabusa; Itokawa; Cosmic-ray exposure ages; Chondrites

Correspondence/findings

Introduction

Numerous remote-sensing techniques coupled with dynamical simulations have provided important constraints on the characteristics and potential origins of near-Earth asteroids (NEAs). While these studies have provided valuable insight, we argue that the only method for validating the conclusions from such work is through analysis of samples returned from these objects. In addition, a key method for understanding the geological and dynamical evolution of asteroids in general, and NEAs in particular, is to develop hypotheses that are testable through the analysis of returned samples. The Hayabusa mission returned samples in the form of numerous small grains of regolith from the surface of asteroid 25143 Itokawa. Research on these returned particles has been a binding force for the sample analysis, remote sensing, and dynamic-modeling communities (Keller and Berger 2014; Langenhorst et al. 2014; Thompson et al. 2014).

We contend that there are two major lines of evidence generated from the analysis of Hayabusa samples that can be used to test hypotheses on the dynamical evolution of Itokawa in the recent geological past: (1) the cosmic-ray exposure (CRE) ages of the returned grains and (2) the overall physical characteristics of these grains. We present a synthesis of existing data from the analysis of Hayabusa samples and chondritic meteorites. We pose new hypotheses and a scenario for the evolution of NEAs that can be tested by future dynamical modeling. We pose a scenario that links seemingly unrelated data, CRE ages of returned regolith grains from Itokawa and those of chondrites to the physical shape of the returned Itokawa grains, and pose processes that affected the dynamical evolution of NEAs with the consequences of producing rounded grains on Itokawa that have young CRE ages and thus affecting regolith gardening.

Cosmic-ray exposure ages, tidal disruptions, and YORP?

CRE ages, either of meteorites or of returned sample from Itokawa, into a context related to the dynamical evolution of asteroids, specifically NEAs, have been a considerable challenge. CRE ages represent two kinds of processes. First, the penetration depth of cosmic rays into rock is on the order of a meter, so meteorites that show damage from isotropic directions, which is often referred to as 4π exposure, are assumed to have been free-floating bodies in space smaller than a few meters in diameter prior to reaching Earth. Here, the CRE ages

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record the time of liberation from their parent bodies (i.e., asteroids) to when they were delivered to Earth.

Damage from a more uniform direction, called 2π exposure, tells us that the sample in question was close to or on the surface of a larger body. Several analyzed grains returned from the asteroid Itokawa have these kinds of CRE ages. If the ages can be correctly interpreted in the context of a process whereby they were exposed near the surface of Itokawa, they can potentially provide us with clues to the dynamical evolution of Itokawa itself.

The classical interpretation for what CRE ages of meteorites record is a catastrophic disruption event through a major collision within the main belt that delivered the meteoroids to resonances and then the Earth (Eugster et al. 2006; Herzog 2005). If this was the main mechanism, however, we should see a plethora of young CRE ages among all meteorite groups, for our purposes chondrites in particular, which is not observed (Bottke et al. 2006).

The 4π CRE ages for different types of chondrites span a wide range (Eugster et al. 2006; Herzog 2005). For the highly lithified ordinary chondrites (OC), most of their ages range between approximately 0.5 and 80 Myr. Interesting peaks in the data are found at 6 to 10 Myr for H chondrites, approximately 40 Myr for L chondrites, and approximately 15 Myr for LL chondrites.

The CRE age distribution of carbonaceous chondrites (CC) is fairly similar to those of ordinary chondrites. The least friable of the CC, the CV, CK, and CO chondrites, have average CRE ages that fall around approximately 13, 23, and 22 Myr, respectively. For the intermediate-strength CR chondrites, a cluster exists around an age of approximately 8 Myr. CRE ages for CH chondrites fall within the range of CRs. CB chondrites have a calculated age of approximately 26 Myr. Finally, the CI and CM chondrites, some of the most friable chondrites, show the youngest CRE ages, with averages of approximately 1.8 and 2.8 Myr, respectively.

The 4π CRE age data for OC and CC demonstrate that some chondrite samples were delivered to Earth in a relatively short time span of a Myr or less, inconsistent with their origin from catastrophic disruption within the main belt (Bottke et al. 2006). As has been discussed in the literature, in addition to catastrophic disruptions, the Yarkovsky effect plays a major role in the orbital evolution of asteroids and meteoroids from the main-belt to near-Earth space (Bottke et al. 2006, for a recent review). The Yarkovsky effect results from the reemission of absorbed solar radiation as thermal radiation, which produces a steady drift in the semi-major axis of the asteroid's orbit. Slow Yarkovsky transportation in the main belt is hypothesized to be the mechanism that explains why meteorites have so few young ages. Thus, the CRE ages of chondrites are thought to describe the time between (1) their origin as small meter-sized meteoroids in the main belt, (2) their subsequent evolution by Yarkovsky thermal forces into a main-belt escape hatch, and (3) their delivery onto planet-crossing orbits that can eventually take them to Earth (see Bottke et al. 2006 for a recent review) or NEA production. As we discuss below, it can also be argued that at least some chondrites delivered to Earth may have come from larger precursors that shed mass impact events or other processes while on Earth-crossing orbits.

To set the stage for our scenario, it is important to review the evidence that links chondrites to asteroids and what we know about the age of the surface of asteroids as constrained from Hayabusa samples. The parent asteroid spectral type for ordinary chondrites was hypothesized to be the S-type asteroids (Binzel et al. 2001; McCoy et al. 2001; Binzel et al. 2010; Nesvorny et al. 2010; Nakamura et al. 2011). The Hayabusa samples provide a key data point for referencing an S-type asteroid to ordinary chondrites, supporting the above hypothesis. Particles returned from the surface of Itokawa are LL chondrite material, ranging from metamorphic type 4 to 6 (Nakamura et al. 2011; Tsuchiyama et al. 2013). In addition, we now have data from samples returned from Itokawa that constrains the age of the surface of that asteroid. The 2π CRE ages for Itokawa samples taken from the surface show a young age of approximately 1 Myr or less, (Meier et al. 2013, 2014), with an upper limit of approximately 8 Myr (Nagao et al. 2011). We note that these data are within the lower range, if not even younger, than the 4π CRE age for ordinary chondrites, indicating that the surface of Itokawa is as young if not even younger than many ordinary chondrites recovered on Earth.

The parent asteroid spectral type for carbonaceous chondrites is hypothesized to be the C-type asteroids (Bus and Binzel 2002; Clark et al. 2011). However, we have no unequivocal evidence that links C-type asteroids to a specific type of carbonaceous chondrite. Therefore, we have no unequivocal evidence of CRE age for material from the surface of C-type asteroids. The goal of the Hayabusa 2 and OSIRIS-REx missions is to return samples from 1999 JU3 and Bennu, respectfully, and provide ground truth on these asteroids through sample analysis.

Explaining the very young CRE age of sample returned from Itokawa requires that we think of all processes that may have affected the asteroids dynamical evolution. We pose the following major questions to explore: (1) Why are the CRE ages for particles found on the surface of Itokawa young? (2) Is there a relationship between the ages of the Itokawa particles and a process that affected and/or affects the evolution of this asteroid? (3) Finally, can we apply what we have learned from the materials returned by Hayabusa to make some wide-scale predictions on the range of CRE ages determined for chondritic materials that are recovered on Earth?

Exploring the questions posed above: it is important to note that the 2π CRE ages of samples from the Moon are on the order of 100 Myr to many hundreds of Myr (Heiken et al. 1991), by far longer than the ages found for grains returned from Itokawa. Thus, the surface of Itokawa is a much more dynamic place than the Moon, and different processes may be shaping the surface. The standard party-line answer to question 1 could be regolith gardening, and that remains a valid hypothesis; at least in part, gardening might be responsible for the age of Itokawa regolith. The question is what processes produce gardening on small bodies like asteroids? The overall morphology of Itokawa is a strong statement that the asteroid has been dynamically disrupted. The issue is what were the affects of this disruption on regolith or regolith production and how does the process that produced the disruption relate to the questions posed above? To explore question 1 and begin to investigate question 2 above, it is important to explore processes other than catastrophic disruption events and the Yarkovsky effect that affect the dynamical orbital evolution of NEAs: the Yarkosky-O'Keefe-Radzievskii-Paddack (YORP) effect and tidal disruptions during planetary close encounters.

The YORP effect is a result of the same physical phenomenon that produces the Yarkovsky effect, namely the reflection/absorption of sunlight and subsequent reemission as thermal radiation. YORP can create a torque that modifies the rotation of small asteroids so they spin up or down, while also affecting their obliquity. In some cases, the YORP effect can add enough rotational angular momentum to change the asteroid shape, with particles, rocks, boulders, etc. moving across the asteroid surface in response to the resulting centrifugal forces (Walsh et al. 2008).

The other dynamical process that can affect the physical properties of NEAs is tidal disruptions from a close flyby to a terrestrial planet. The tidal forces of a planet acting across the asteroid passing within a few planetary radii of a planet like Earth or Venus can entirely disrupt or distort the asteroid (Richardson et al. 1998). Nesvorny et al. (2010) argued that tidal effects could disturb the surface of a NEA in a number of ways: (1) The interior structure of a rubble-pile NEA might find a new equilibrium by rearranging its components; this could result in landslides or displacement of near-surface material, etc. (2) Tidal stresses applied to a fractured interior could produce seismic shaking, allowing fresher material to reach the surface. (3) The tidal torques could add or subtract enough rotational angular momentum to cause it to shed or rearrange its surface regolith. We argue that all of these processes could have contributed to producing new regolith on the surface of Itokawa and thus explain the young CRE ages of returned sample.

Nesvorny et al. (2010) also explored how tidal forces might resurface NEAs in the context of space weathering. It has been found that many fresh-looking, non-space-weathered ordinary-chondrite-like bodies called Q-type asteroids have orbits similar to asteroids that would be most likely to undergo tidal encounters. By tracking asteroids during close encounters with Earth and Venus, and then comparing these results to the orbital distribution of space-weathered S-types and Q-types in the NEA population, Nesvorny et al. (2010) were able to calculate the timescale of resetting by space weathering for the asteroid population. The order of their timescale, approximately 1 Myr at 1 AU for objects making typical passes of 5 planetary radii near Earth or Venus, represents the interval during which a fresh Q-type affected by space weathering will remain a Q-type; at least the dominant signature from the asteroid surface is from materials that produce Q-type spectra.

To explore question 2 from above, we hypothesize that the physical processes we have discussed that affect near-Earth objects, such as YORP or tidal encounters, may provide an explanation for the short CRE ages of the grains found on Itokawa. One end-member possibility is that the CRE age data suggest that the last major breakup and reaccretion experienced by Itokawa occurred approximately 8 Myr (upper limit), with subsequent processing occurring at potentially approximately 1.5 Myr or <0.5 Myr (or at all ages). During these breakups, either as a result of YORP or tidal disruptions, or a combination of these processes, Itokawa would have had its surface reshaped and it is highly likely that it lost mass (Richardson et al. 1998; Walsh et al. 2008; Binzel et al. 2010; Nesvorny et al. 2010).

Within our discussion, we have set the stage for a scenario that can provide an answer to question 3 posed above: extending our reasoning to meteorites, we hypothesize that YORP and tidal disruption had the net effect of causing NEAs to shed mass, with perhaps some of this lost mass arriving to the surface of Earth (Richardson et al. 1998; Walsh and Richardson 2006). Thus, we hypothesis that chondrites (or other meteorites) that have young 4π CRE ages can be explained not only from an impact event, but as having been the result of mass loss from their parent asteroid(s) due to YORP spin-up or tidal disruption. A range of CRE ages within chondrites or chondrite type could be reflecting whole-scale restructuring of their parent asteroids due to YORP or tidal disruption, potentially mixing rock as cobbles, boulders, etc., to produce a combination of young (fresh even) and older regolith. We can extend this scenario to grains returned from Itokawa being the product of mixing due to YORP or tidal disruption as discussed above.

Geologic high-energy environments on Itokawa: abrasion of grains and YORP effects?

Based on their overall general shape, grains returned by Hayabusa from Itokawa have been divided into two main groups: angular and rounded (Tsuchiyama et al. 2011, Tsuchiyama et al. 2013). The presence of angular grains on the surface of Itokawa was not unexpected. However, the presence of rounded grains is a surprise. The presence of rounded rock or minerals in any geological setting on a planet indicates a geologically high-energy environment - one that is or was actively moving material resulting in mechanical weathering, which must be more than a one-time event in order to turn angular grains into rounded ones. Mechanical weathering of rocks or minerals is a differential process that in part depends on characteristics such as composition of the material and in the case of rocks the level of their lithification. Such geologically high-energy environments on planetary surfaces are produced by wind- or water-dominated geological settings, even ice-dominated such as glacial movement. However, on an airless body such as Itokawa, weathering of material on surfaces cannot be the product of movement of any kind of fluid, particularly on the surface of bodies. Whatever mechanism or combination of mechanisms produced the rounded grains, the young CRE ages of the returned grains indicate that they were formed or exposed near the surface relatively recently and science must explain their existence. We thus pose two questions directly related to the rounding of grains on airless bodies such as Itokawa: (1) What geologically high-energy environments exist or existed that could physically weather rock to produce rounded grains on the surface of an asteroid? (2) Does the overall physical shape and characteristics of the Itokawa particles constrain the dynamical evolution of Itokawa and, by extension, other asteroids?

Exploring the questions posed above: a geological high-energy process and one known to have occurred on asteroids is macro- or micro-impacts, which without question is a powerful process for weathering of materials and the production of regolith. Tsuchiyama et al. (2011, 2013) hypothesized that the geologically high-energy environment needed to produce the physical weathering of rounded Itokawa grains was the byproduct of shaking of the asteroid due to impacts. We envision that what is implied by this hypothesis is that grains repeatedly migrate within the regolith due to repeated impacts. Whereas we cannot completely refute this hypothesis through quantitative argument, qualitatively the number and size of impacts on the surface of such small asteroids as Itokawa that could produce an environment energetic enough to physically weather particles seems unlikely. In addition, as discussed above, Itokawa's surface is not littered with impact craters (Michel et al. 2009) adding additional qualitative support to our argument. To date, however, no quantitative modeling has been performed to test the impact hypothesis, and thus, we cannot nor do we completely rule it out as a contributor to grain production through mechanical weathering.

To explain the physical weathering of rounded grains on Itokawa, we hypothesize that the dominant mechanism is from instabilities in the rotational axis and, most importantly, YORP effects. As was argued by Walsh et al. (2008), YORP can play a significant role in evolving the regolith on the surface of small asteroids. Whereas we also cannot discount the potential importance of tidal forces affecting asteroids, and certainly it may have produced angular fragments of rocks and regolith, YORP occurs steadily over the lifetime of the asteroid, compared to the whole-scale stochastic restructuring of an asteroids physical shape from tidal forces alone. The spinning-up of an asteroid due to YORP would produce an environment where material is colliding frequently and thus physically weathering, both on the spin-up and in the reaccretion. Once an asteroid is reformed by YORP, we speculate that the surface of the object may have new slopes; thus, regolith that exists and new regolith that forms could be migrating downslope, as may be true for asteroid Bennu (Lauretta et al. 2014), which could have the net effect of weathering small grains to become rounded. For Itokawa, it is not clear if grains could be migrating downslope to the Muses Sea. Miyamoto et al. (2007) argued that grain migration might have been due to gravity forcing landslides or grain convection on the asteroid surface. They also discussed the potential for grain movement due to tidal forces. We speculate that the roundness of the grains may have been largely related to grain collisions resulting from YORP-driven processes, which may also have caused major mass-wasting processes such as landslides (Miyamoto et al. 2007). Tidal forces, however, are most likely not responsible for multiple reshaping of regolith grain from angular to rounded. If small, dust-sized grains are to be rounded, it may require multiple or continuous restructuring of the asteroid, and that we argue is consistent with YORP.

It is not clear that Itokawa went through or could experience YORP and some debate exists within the literature (Kitazato et al. 2007; Breiter et al. 2009; Lowry et al. 2014; Mazrouei et al. 2014; Scheeres et al. 2007). We contend that the existence of rounded grains is additional evidence that Itokawa experienced YORP. Indeed, some of the boulders on the surface also appear rounded, which may provide additional evidence for a geological high-energy environment created by YORP.

As discussed above, all particles returned by Hayabusa thus far investigated have relatively young CRE ages. We have discussed a potential mechanism that could have produced rounded grains. It would be remiss of us if we

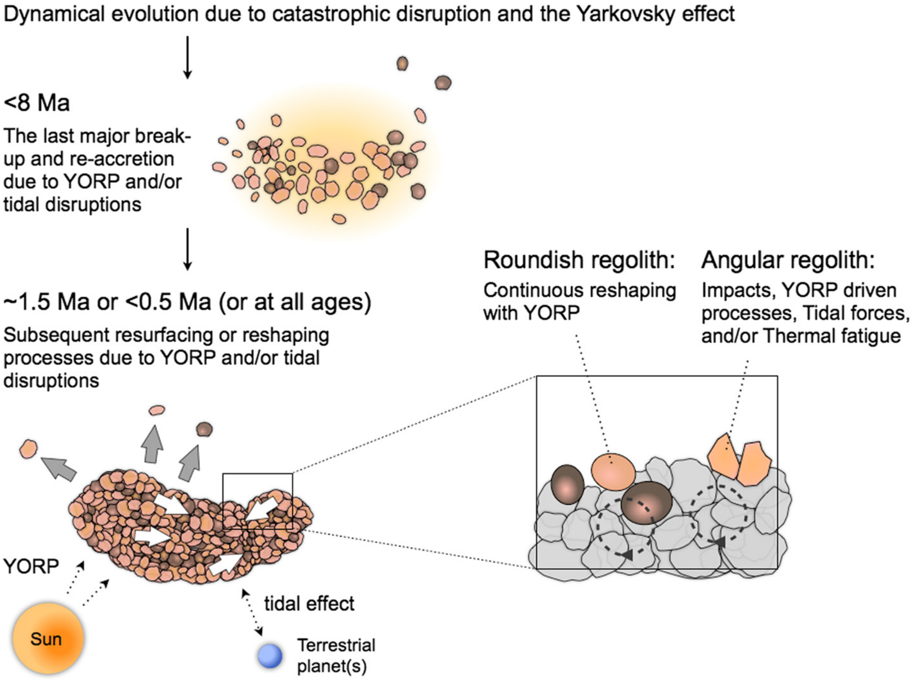

Figure 1 A schematic drawing summarizing the potential evolution of the surface of Itokawa.

did not also apply our reasoning to the production of angular grains. Angular regolith grains could have been produced from a number of mechanisms: (1) impacts, (2) YORP-driven processes, (3) tidal forces, and/or (4) thermal fatigue (Murdoch et al. 2012; Delbo et al. 2014). Constraining which one (or combination of processes) was the dominant mechanism may require a data set that carefully compares the CRE ages of rounded grains with those that are angular. We predict that there should be a higher abundance of rounded grains with slightly older CRE ages than angular grains due to the fact that time is needed to produce the physically weathered rounded grain from an angular one.

Future missions and predictions on the nature of the returned sample

In the future, Hayabusa 2 and the OSIRIS-REx missions will return samples from two NEAs, 1999 JU3 and Bennu that are hypothesized to be very different chemically from Itokawa and certainly, as asteroids, have different overall shapes. We predict, however, that the CRE ages of the returned materials will be young, closely matching that of CI and CM chondrites (Clark et al. 2011), which are proposed as the closest analogs to type C asteroids. We further predict that some of the particles returned will have experienced weathering to produce rounding, and we further speculate that, based on our reasoning above, because of the overall shape of 1999 JU3 and Bennu, the proportion of rounded grains to angular will be higher than material returned from Itokawa. Material may be continuously migrating from polar to the equatorial regions on these asteroids with the overall shape of these objects, at least for Bennu, having been shaped in part by YORP (Nolan et al. 2013). It is one of the goals of these missions to test the hypotheses put forth in this paper through the analysis of the returned samples and for modelers to make additional predictions on the affects of YORP and tidal disruptions that will be tested by the returned samples.

Summary

We have proposed that the relatively young CRE ages of samples returned from Itokawa may be reflecting either YORP or tidal disruption. Given the fact that rounded grains returned by Hayabusa require a geological high-energy environment for their production and that YORP has the potential for repeatedly affecting the surfaces of asteroids over time whereas tidal disruption does not, we propose that YORP was a major process that helped produce and shape the regolith on Itokawa (Figure 1). Furthermore, we extend our reasoning to predict that mass loss from NEAs that occurs during YORP is responsible, at least in part, for delivering chondrites with young CRE ages to Earth.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

HCCJr, DSL, KJW, ST, and WFBJr contributed to the interpretation and preparation of this manuscript. All authors read and approved the final manuscript.

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