Two-Step Simulation for the Formation of Asteroid Itokawa from the Restricted Three-Body Problem to the Multi-Body Problem

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This paper studies a formation of Asteroid Itokawa in 2-dimension, dividing the formation process into two steps. The first step is a collapse of parent bodies and the second step is the attachment of small fragments to the early Itokawa that is created by the first step. In the first step, the aggregation of fragments after a head-on impact of two parent bodies is investigated by utilizing the N-body problem with the spring-dumper system. The radius of each fragment and the total mass in the system are set to be 32 meters and 10 times as large as Itokawa, respectively. It is found in the first process that the collision of two parent bodies allows a formation of the early Itokawa that is made by a soft contact of two primary bodies. In the second step, 500 fragments are randomly positioned around the early Itokawa and their motions are numerically analyzed by applying the circular restricted three-body problem. It shows that the population of fragments around the early Itokawa is almost constant regardless of the Jacobi integral, the conserved value in the problem. It implies that fragments may play a role in creating the current shape of Itokawa.

Key Words: Rubble Pile, Contact Binary, Circular Restricted Three-Body Problem, N-Body Problem

1. Introduction

The exploration of the Hayabusa spacecraft on Asteroid Itokawa in 2005 is one of sensational space-missions in the world. Due to this exploration, recent studies based on photometric and radar observations reveal the peculiar characteristics of Itokawa, whose picture is shown in Fig. 1. From the knowledge, some researchers discuss how Itokawa is developed. Saito et al.1) point out that Itokawa has rubble-pile structure whose elements are held together by self-gravity. Fujiwara et al.2) present that Itokawa forms due to a soft contact of two primary bodies which are shaped after a collapse of parent bodies. The current paper focuses on the evolution process of Itokawa, using astrodynamics.

As for the important results of scientific aspects, Fujiwara et al.2) argue that Itokawa is developed by the following processes. First, a collapse of parent bodies occurs, followed by a formation of two primary bodies. Second, these two primary bodies softly contact, the result of which is the formation of the contact binary body, namely the early Itokawa. At last, after the attachment of fragments to the early Itokawa, the current Itokawa is developed. This evolution process is shown in Fig. 2. The current paper adopts their arguments in order to analyze the evolution. In addition, as shown in Fig. 3, to clarify the discussion the analysis in this paper is divided into two steps. The first step that is enclosed by the red dot line is the process from the collision of two parent bodies to the formation of the contact binary body, or the early Itokawa. Later, the contact
binary body is simply called the early Itokawa. The second step, on the other hand, is indicated by a purple dot line and is the process of attachments of fragments to the early Itokawa. Our analyses are executed numerically; however, it should be noted that the simulation is implemented in 2-dimension because of our computer capacity.

The first step is the case where a collapse of the parent bodies happens, followed by a soft-contact formation shaping the early Itokawa. Here is used the N-body problem with the spring-dumper system. It is also assumed that each fragment has a circular shape; the planer shape is due to the current study in 2-dimension. The collision between fragments can be expressed by the spring-dumper system. As for the initial condition, the two parent bodies that are supposed to be rubble piles have specific velocities so as to have “head on” collisions between them. The total number of fragments in each simulation is set 500 and the total mass is equal to 10 times of Itokawa mass.

The second step focuses on the motion of fragments in orbit about the contact binary body, or the early Itokawa, as shown in Fig. 3. Since the early Itokawa can be considered to be much larger than fragments flying nearby, the mass of each fragment can be assumed to be negligible. Due to this assumption, it is possible to model the early Itokawa by the two-mass body that two finite masses flying around each other in circular orbits are connected by a massless rod. This model allows us to apply the circular restricted three-body problem (CR3BP) to this problem. The analysis is also numerically executed with 500 fragments evaluated by Jacobi integral.

The current paper shows the first step in the chapter 2. The second step is discussed in the chapter 3. To clarify the discussion it is defined that the term “fragment” is used to indicate an element such as a rock or a piece of dust, while the term “body” means a body having rubble-pile structure.

2. The First Step

2.1. The methodology of computation

To investigate the motion of each fragment the N-body problem is applied to this problem. In the current study, a collision between fragments is expressed by the spring-dumper system. By taking into account this effect, the equation of motion about \( i \) th fragment can be written by

\[
m_i \frac{d^2\mathbf{r}_i}{dt^2} = -\sum_j \frac{G m_i m_j \mathbf{r}_{ij}}{d_{ij}^3} \mathbf{e}_i - \sum_j k (\mathbf{r}_{ij} \cdot \mathbf{e}_i - d_{ij}) \mathbf{e}_i + c (\mathbf{v}_i - \mathbf{v}_j) \cdot \mathbf{e}_i \mathbf{e}_i,
\]

where the subscript \( j \) indicates the fragment that flies independently and thus does not contact with the \( i \) th fragment, while the \( s \) th fragment attaches with the \( i \) th fragment and is affected by the spring-dumper system. The first term on the right-hand-side is the gravitational force, while the second term describes the spring-dumper force. The system expressed by Eq. (1) is drawn in Fig. 4. Here is assumed that each fragment should have a specific radius, i.e. 32 meters; therefore, a collision between fragments is considered to occur when the distance between the center of mass of the fragments becomes less than the sum of their radii. If this condition is satisfied, the spring-dumper force, the sum of repulsion force proportional to the velocity and that to the distance, has an influence upon these fragments. Note that to simply our discussion here the gravitational interaction between the \( i \) th and \( s \) th fragments is neglected. It is because in the case of the collision, the distance between the center of mass of them becomes too short, the result of which dramatically makes the accuracy of numerical simulation deteriorated. The other way of avoiding this issue may be to illimitably narrow the step size of our computation; however, our computational capacity is not enough to do that. From this point of view, the current paper adopts the assumption that neglects the gravitational effect between the \( i \) th and \( s \) th fragments. In addition, the following assumptions are also considered in this study.

First, the simulations are executed in the two-dimension. Since the current study neglects the friction that affects in the

![Fig. 1. Itokawa taken by the Hayabusa spacecraft.](image1)

![Fig. 2. Process map of the evolution of Itokawa.](image2)

![Fig. 3. Separated processes of the Itokawa evolution.](image3)
circumferential direction, as shown in Eq. (1), this assumption becomes valid because the motion of fragments is axisymmetric. Due to this assumption, the alternative density \( \rho' \) for the 2-dimensional analysis is defined by

\[
\frac{4}{3} \rho a^3 = \rho a' a' \implies \rho' = \frac{4}{3} \rho a.
\]

where \( \rho \) indicates not the grain density but the bulk density of Itokawa as being 1.9 g/cm\(^3\).

Second, the rotation of fragments is not considered in the current study. This assumption allows the angular momentum to be always kept zero during the computation.

In the simulation, the initial collision velocities are given so that the parent bodies have a “head-on” collision that occurs along the line passing through both the center of mass of these bodies. For the computation, 500 fragments are used and the total mass is 10 times as much as the Itokawa mass. Again, the radius of each fragment is defined as 32 meters.

\[
\text{Fig. 4. Interaction between fragments in the system.}
\]

2.2. Result of the first-step analysis

Our study examines 30 cases, using the simulation technique that is mentioned above. The simulation time is set 2.5 times of the Itokawa period, i.e. 30.33 hours. The mass ratio of each 10 cases is \( M_1 : M_2 = 4:1 \), \( 3:2 \), and \( 1:1 \), respectively, where \( M_1 \) is one parent body and \( M_2 \) is the other. Then, in every 10 cases, the initial velocity of the collision is changed from 0.0 to 1.22 m/sec. To categorize our results clearly the magnitude of the initial velocity is defined by percentage with respect to 1.22 m/sec: the minimum being 0, and the maximum being 100.

Initially, let us consider shattering-phenomena caused by the initial collision. It can be easily imagined that whether each fragment can get together or unfortunately fly away depends on the initial total-energy of this system. This is true; the larger the collision energy becomes, the more the bodies shatter. Note that the total energy cannot be conserved because of the dumper effect in the system. Fig. 5 indeed shows our interpretation about the velocity clearly. The case from A to C indicates the result of the mass ratio, \( 4:1 \), \( 3:2 \), and \( 1:1 \), respectively. The vertical axis shows how many bodies exist in the system and the horizontal axis is the dimensionless time, the time divided by \( T \). The dot lines indicate the results of the case for \( v_p = 40 \) and the bold lines are for \( v_p = 100 \).

It is simply found that the number of bodies strongly depends on the collision velocity because it dramatically varies in the small range of the initial velocity \( v_p \) that is from 40 to 100, the difference of which is less than 1 m/sec. It implies that in this range, there is a border between reaggregation and shatter after the collision. It is important to compare this result with one of prior works. Leinhardt et al.3) investigate the feature of collisions of two spherical kilometer-size bodies. They conclude that the velocity for 1 to 2 m/sec causes a collision of two parent bodies to make other rubble piles, while higher velocities allow parent bodies to utterly shatter. Compared to their works, the result in the current study may be somewhat small. This difference comes from the fact that our target is smaller than that in their work. In addition, it is also caused by our simplified discussion that focuses on only the 2-dimensional dynamics. From this assumption, it can be considered that the propagation of kinetic energy occurs only on the planer motion in our study, while the 3-dimensional dispersion of the total energy appears in their work. As a result, our case needs less energy to shatter the parent bodies than the 3-dimensional computation. In the following discussions, our results are shown by taking into account this fact.

\[
\text{Fig. 5. Time profile of the number of bodies.}
\]

Again, it is found from Fig. 5 that after the collision, the number of bodies increases rapidly and reaches the peaks around 0.25 of our time scale. Then, it decreases little by little. This tendency is more noticeable at \( v_p = 100 \) than \( v_p = 40 \). It is because in the case for \( v_p = 100 \), fragments fly far away from the center of mass and cannot attach other fragments, while in the case for \( v_p = 40 \), many bodies form after a mild shattering caused by the collision, orbit around the center of mass, and keep their shape. Here are shown only two cases for \( v_p \) because the similar trends that the number of bodies depends on \( v_p \) can be seen in other cases. Let us discuss the difference caused by the mass ratio. In the current study, all the cases have similar trends with respects to the number of bodies and the time-oriented feature of shattering. This fact implies that when the parent bodies are circles in the 2-dimensional analyses (or spheres in the 3-dimensional analyses), the magnitude of shattering depends on the energy of parent bodies, i.e. the initial velocity of a collision, rather than the mass ratio.

The formation of the early Itokawa is now discussed.
According to Fig. 1, Itokawa consists of a small head and a large body. The size of these parts is estimated from the small model of Itokawa, as shown in Fig. 6. From this, the ratio of the head to the body is defined as 3:7. By using this ratio, the formation of the early Itokawa is evaluated. In this paper, it is considered to be the formation of the early Itokawa if after the collision, one primary body composed of 30 to 70 percent of the current Itokawa’s mass attaches to the other of which mass is also within that range.

Table 1 indicates the result of this evaluation. As mentioned above, it shows the case for $M_1:M_2 = 4:1$, $3:2$, and $1:1$. $N_m$ is the maximum number of the bodies in each simulation, $N_a$ is the maximum number of the bodies consisting of more than 30 percent of Itokawa mass, and $N_f$ indicates the number of the formation of Itokawa defined above. Firstly, increasing $v_p$ results in the increment of $N_m$ in all mass ratios. $N_a$ corresponds to the peak of the value shown in Fig. 5 and is apparently independent on the mass ratio $M_1:M_2$. Next, it is useful to see $N_f$ because it directly indicates the possibility of the formation of the early Itokawa that may be caused by the soft contact of the two primary bodies, each having 30 to 70 percent of the Itokawa mass. In every mass ratio, $N_f$ peaks between $v_p$ being 60 and that being 80. It means that for $60 \leq v_p \leq 80$, there is a border of the formation of the early Itokawa. In other words, if $v_p$ is bigger than this range, the body’s size becomes smaller and the number increases. On the other hand, when $v_p$ is less than that, the result turns around. $N_f$ indicates the formation of the body which experiences the same scenario as Itokawa has. The region of $v_p$ where $N_f = 1$ corresponds to that of the peak value of $N_a$. This result indicates that if $N_a$ is increased, $N_f$ is also increased.

One example of the simulation that shows the Itokawa formation is drawn in Fig. 7. The condition of the simulation is $M_{pe}:M_{pr} = 4:1$ with $v_p = 70$. Fig. 7A is the case just before the collision of the parent bodies, Fig. 7B is just after the collision, and Fig. 7C is at the end of the simulation. The contact binary, enclosed by the red circle in the right upper side in Fig. 7C, experiences the evolution to become the early Itokawa. Note that although the current study identifies and recognizes the formation of the early Itokawa numerically, this is just one of reasonable explanations about the formation. Thus it is necessary to continue further detailed verifications to apply our study to the real case.

3. The Second Step

3.1. The equation of motion in this system

In the second step, the motion of the small fragments in orbit about the early Itokawa is discussed. As well as the first step, the analysis of the second step is also numerically executed in 2-dimension. In this step, the early Itokawa is supposed to be the two-mass system that two fine masses flying around each other in circular orbits are rigidly connected by a massless rod. The model is shown in Fig. 8. The equation of motion about a fragment in this system is described as

$$\frac{d^2x}{dt^2} = 2\omega \frac{dy}{dt} = V_x,$$

$$\frac{d^2y}{dt^2} + 2\omega \frac{dx}{dt} = V_y,$$

Table 1. List of the simulation about the first collision.

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<th>$v_p$</th>
<th>$N_m$</th>
<th>$N_a$</th>
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Fig. 7. Simulation for $M_{pe}:M_{pr} = 4:1$, $v_p = 70$ (−0.86 m/sec).
This equation is expressed in the rotating frame. \( x \) axis passes through the center of mass of each body and \( y \) axis is perpendicular with \( x \) axis. Here, the subscript 1 and 2 indicate each finite mass, or each circle in 2-dimension. Subscript 3 shows a mass-free fragment in orbit about the early Itokawa. It is simply found that the equation of motion is very similar to that of the CR3BP except that a new parameter \( \omega \) appears in the system.

\[
V = \frac{1}{2} \omega^2 (x^2 + y^2) - \frac{Gm_1}{d_{13}} + \frac{Gm_2}{d_{23}} + \frac{1}{2} \left( v_x^2 + v_y^2 \right).
\]  

(4)

This analysis should be done in the future. The simulation result for \( JC = 20 \) is shown in Fig. 11.

3.2. The motion of fragments around the early Itokawa

3.2.1. The Jacobi Integral

To discuss the fragment motion around the early Itokawa numerically it is useful to apply the Jacobi integral which is described by

\[
C_J = -\omega^2 \left( x^2 + y^2 \right) - 2 \left( \frac{Gm_1}{d_{13}} + \frac{Gm_2}{d_{23}} \right) + \left( v_x^2 + v_y^2 \right).
\]

(5)

Note that \( C_J \) in the current paper has an opposite sign to the traditional expression. Our numerical analysis evaluates the features of the fragment motion by varying the velocity in the rotating frame. In this way, it is advantageous to use \( C_J \) expressed by Eq. (5) because it directly indicates the strength of the velocity. Now, when the configuration of Itokawa is applied to Eq. (5), the contour of the zero-velocity curve can be drawn by the blue dot lines, as shown in Fig. 9. The red dot line, on the other hand, is defined by the extremal value as being

\[
\frac{\partial C_J}{\partial x} = 0 \quad \text{and} \quad \frac{\partial C_J}{\partial y} = 0.
\]

(6)

The early Itokawa lies inside the innermost blue dot line. Kawaguchi et al.\(^4\) show the red dot line is the boundary where the trend of the fragment motion changes. From this fact, in the following section, how many fragments stay inside the curve expressed by Eq. (6), simply called the boundary later, is studied.

3.2.2. Result of the second-step analysis

The number of fragments that stay inside the boundary is discussed. If many fragments fly in this area, the probability that they attach or are going to attach to the early Itokawa becomes larger. On the other hand, if there are few fragments, the result turns around. Here, each fragment is categorized by \( C_J \) and the population around the early Itokawa is investigated. The current discussion omits the case of \( C_J < 0 \) because the case where each fragment has immovable area around the system implicitly predicts which fragments can attach to the early Itokawa.

500 fragments are used in all simulations. And again, based on the previous chapter, it is assumed that \( m_1 = 0.7M \) and \( m_2 = 0.3M \). The distance between the center of mass is 267.5 m, equal to the maximum major semiaxis of Itokawa. Their initial velocities in each simulation are given randomly, but so as to keep \( C_J \) constant in each simulation. This paper sets the value of \( C_J \) from 0.0 to 28.0. To express the attachments of fragments to the early Itokawa the impact detection is defined as an ellipsoid whose semimajor axes are 267.5 m and 147 m. If a fragment enters into this area, it is considered that it attaches to the early Itokawa.

There are two types of fragments inside the boundary: some attaching to the early Itokawa, and the others continuing to fly around it. In the current paper, both of them are counted as the fragments staying in the area. All simulations are executed in 100 times of the Itokawa period, equal to be around 1200 hours in the real time.

It is now analyzed how \( C_J \) affects upon the number of fragments inside the boundary. The result is shown in Fig. 10. The vertical axis describes the ratio of the number of fragments inside the boundary to the total number at the end of the simulation time, i.e. \( t = 100 \) (dimensionless). The horizontal axis indicates \( C_J \). It is found that the number of the fragments is almost constant even if \( C_J \) is changed. In other words, the population of fragments does not change even if the kinetic energy and the potential energy are changed. Instinctively, increasing \( C_J \) implies that the velocity in the rotating frame increases and the fragments with such a large \( C_J \) can fly away from the early Itokawa. Our result, however, is different from this interpretation. For \( 0 < C_J < 28 \), many fragments tend to contact with or fly around the early Itokawa. From this fact, it can be found that in this case, the fragments can still attach to the early Itokawa and modify the shape, regardless of any values of \( C_J \). The cases of \( C_J \) being more than 28, on the other hand, may show that the number of fragments inside the boundary decreases. This analysis should be done in the future.

The simulation result for \( C_J = 20 \) is shown in Fig. 11.
Each image describes the motion of fragments at $t = 0$, 50, and 100, respectively, in our time scale. At $t = 0$, the position of fragments is set randomly; the velocity is also randomly defined, but so as to satisfy $C_J = 0$. At $t = 50$, 100, the population is almost same and it can be considered that the simulation becomes static. In this paper, only this case is described because different trends in other cases cannot be observed.

In the current work, the formation of Itokawa is discussed in 2-dimension by dividing the evolution process into two step approaches.

In the first step, the fragment motion after a collapse of two parent bodies is studied. The collapse of the parent bodies is supposed to be a collision of two rubble piles. In order to discuss this step, the N-body simulation with the spring-dumper system is used. When the total mass in the each simulation is set 10 times of the Itokawa mass and the mass ratio of one parent body to the total mass is changed, it is found that the initial velocity is a more important factor than the mass ratio. To form an asteroid that experiences the same scenario as Itokawa evolves the initial velocity should be around 1.0 m/sec, the amount of which is relatively small but necessary to create primary bodies having 30 to 70 percent of the mass of the current Itokawa. It implies that the early Itokawa results from a soft contact, rather than a devastate crash of bodies.

In the second step, the motion of small fragments around the early Itokawa is discussed by using the numerical analysis. The early Itokawa is assumed to be the two-mass body connected with each other. It is focused on how many fragments exist inside the boundary drawn by the extremal value of the potential. Regardless of varying Jacobi integral, the number of fragments inside the boundary does not change. This means that after the formation of the early Itokawa, the attachment of a variety of fragment may also play a role in shaping the current Itokawa.

It can be inferred from the current study that there is a possibility that the early Itokawa is formed by a soft collision of two parent bodies followed by a smooth contact of two primary bodies. Eventually, small fragments attach to the early Itokawa, shaping the current Itokawa.

Note that, however, there are still problems remain in our analysis. First, our current study focuses on the 2-dimensional dynamics. This neglects the effects of the out-of-plane motion. As an example, the collision velocity in 2-dimension is smaller than that in 3-dimension. It comes from the fact that the kinetic energy does not propagate to the out-of-plane direction. From this point, our simulation should be improved as future works.

Next, the first step adopts the assumption that the parent bodies are rubble piles. However, there is a possibility that these asteroids are monoliths. In the second step, the two-mass model is used to describe the shape of the early Itokawa. However, there is an uncertainty of the shape. From this reason, the verification of our current analysis must be done. Furthermore, the simulation in the case of higher $C_J$ should also be studied.

4. Discussion & Conclusion

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Next, the first step adopts the assumption that the parent bodies are rubble piles. However, there is a possibility that these asteroids are monoliths. In the second step, the two-mass model is used to describe the shape of the early Itokawa. However, there is an uncertainty of the shape. From this reason, the verification of our current analysis must be done. Furthermore, the simulation in the case of higher $C_J$ should also be studied.

4. Discussion & Conclusion

In the current work, the formation of Itokawa is discussed in 2-dimension by dividing the evolution process into two step approaches.

In the first step, the fragment motion after a collapse of two parent bodies is studied. The collapse of the parent bodies is supposed to be a collision of two rubble piles. In order to discuss this step, the N-body simulation with the spring-dumper system is used. When the total mass in the each simulation is set 10 times of the Itokawa mass and the mass ratio of one parent body to the total mass is changed, it is found that the initial velocity is a more important factor than the mass ratio. To form an asteroid that experiences the same scenario as Itokawa evolves the initial velocity should be around 1.0 m/sec, the amount of which is relatively small but necessary to create primary bodies having 30 to 70 percent of the mass of the current Itokawa. It implies that the early Itokawa results from a soft contact, rather than a devastate crash of bodies.

In the second step, the motion of small fragments around the early Itokawa is discussed by using the numerical analysis. The early Itokawa is assumed to be the two-mass body connected with each other. It is focused on how many fragments exist inside the boundary drawn by the extremal value of the potential. Regardless of varying Jacobi integral, the number of fragments inside the boundary does not change. This means that after the formation of the early Itokawa, the attachment of a variety of fragment may also play a role in shaping the current Itokawa.

It can be inferred from the current study that there is a possibility that the early Itokawa is formed by a soft collision of two parent bodies followed by a smooth contact of two primary bodies. Eventually, small fragments attach to the early Itokawa, shaping the current Itokawa.

Note that, however, there are still problems remain in our analysis. First, our current study focuses on the 2-dimensional dynamics. This neglects the effects of the out-of-plane motion. As an example, the collision velocity in 2-dimension is smaller than that in 3-dimension. It comes from the fact that the kinetic energy does not propagate to the out-of-plane direction. From this point, our simulation should be improved as future works.

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References


