

Earth impact probability of the Asteroid (25143) Itokawa to be sampled by the spacecraft Hayabusa

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Abstract

The Japanese spacecraft Hayabusa is planned to reach the Asteroid Itokawa in September 2005, and to bring back some samples of its surface to Earth in 2007. We have studied the future possible evolution of this asteroid by integrating numerically over 100 Myr a set of 39 initially indistinguishable orbits (*clones*), obtained either by small variations of the nominal initial conditions, or by using different computers (introducing different round-off errors). The results indicate that an Earth impact of this 500-m-size asteroid is likely within a million years, which is only a factor of four larger than the average impact frequency of asteroids of this size. The mission Hayabusa may thus sample a good candidate for being among the next 500-m-size Earth impactors.

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1. Introduction

The Asteroid (25143) Itokawa is the target of the Hayabusa mission (MUSES-C) operated by the Japanese Aerospace Exploration Agency (JAXA) and launched in May 2003 (Fujiwara et al., 2000). The samples to be brought back to Earth will be the first unaltered material from asteroids that will be analyzed in laboratory. The knowledge of physical properties of small bodies can provide important clues to the composition of the solar nebula before planets were formed. Indeed, probably only a few large asteroids such as Vesta and Ceres have experienced high temperatures causing significant thermal evolution, while most small bodies could neither experience such high temperatures during their formation nor retain any atmosphere due to their small sizes. As a consequence, most asteroids and comets are assumed to be relatively pristine objects, compared to the

larger and differentiated planetary bodies, their satellites and the largest asteroids. Moreover, it is recognized that impacts by small bodies cause a significant hazard to the future of human kind. Information on the physical properties of a potential impactor and early estimates of the timescale before the event are required to develop efficient mitigation strategies (Gritzner and Kahle, 2004). The Asteroid Itokawa, from which samples will be analyzed, belongs to the population of near-Earth objects (NEOs) which includes the potentially threatening bodies. Therefore, it is interesting to determine whether Itokawa has a non-negligible probability to collide with our planet. The analysis of the data provided by the Hayabusa mission would then take another importance. An impact by an object of this size may cause regional damages if not global ones depending on its physical properties and on the surface properties of the impact site (Toon et al., 1997).

In this paper, we provide an estimate of the collision probability of Itokawa with planets based on a statistical investigation of its future possible evolution.

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2. Method of investigation

The major difficulty to predict NEO evolutions is that the orbits of planet-crossing objects are very chaotic, with Lyapunov divergence times $t_L \approx 10^2$ yr (e.g., Whipple, 1995; Tancredi, 1995), owing to the sensitive dependence of the orbital changes caused by planetary encounters on the pre-encounter orbit. This is particularly true for Itokawa whose short-term chaotic nature has been demonstrated (Yoshikawa, 2002). Consequently, computed evolutions are not deterministic predictions of the real evolutions over times much longer than the Lyapunov time t_L . Moreover, planet-crossing orbits are also sensitive to the assumed physical model of the Solar System, to the integration algorithm and to the round-off features of the computer. Small changes to any of these options imply that beyond a few time t_L , the computed orbits completely “lose memory” of their common origins. They are just “possible evolutions,” which are nonetheless very useful to identify the most important dynamical mechanisms which *may* affect the real orbit, or to make statistical estimates on the object’s lifetime, encounter rate and so on. To increase the statistical significance of our study, we thus considered the *nominal object* defined with its measured orbital parameters listed in asteroid ephemerides, and also a sample of *clones*, i.e., initially “indistinguishable” orbits obtained by either adding or removing the last digit of one of the orbital elements at a time, or by using different computers (implying different round-off errors) to perform the actual integrations. Hence, in addition to the nominal orbit, we defined 12 clones by changing each of the six orbital elements at a time (called, e.g., Itokawa Ia+, Ia–, where a is the semimajor axis and the sign indicates if the last digit was increased or decreased by unity) and 26 more clones (called, e.g., Itokawa IIa+ and IIIa+) by repeating the integrations on two other computers. In total, we thus obtained 39 clones and we computed their orbital evolutions over 100 Myr, within which only 4 of them survived and 35 collided with a planet, the Sun or were ejected outside Saturn’s orbit. We adopted a purely gravitational model of the Solar System, including all the planets except Pluto.

Using these initial conditions, we computed the long-term possible evolution of Itokawa by using a numerical integrator that already allowed us to study the evolutions of some NEOs (Michel et al., 1996a, 1996b). It consists of a Bulirsch–Stoer variable step-size algorithm (Stoer and Bulirsch, 1980), optimized for dealing accurately with planetary close approaches, and adapted by us for recording accurately the miss distance corresponding to the encounters, despite the discrete time steps used to compute the orbits (Michel et al., 1996a). The accuracy of this integrator is computationally expensive but it is required to have enough confidence, particularly for orbits subjected to rapid changes. However, it limits the number of clones that can be integrated at reasonable computational expense.

3. Possible future orbital behavior of Itokawa

The results of the integrations of the orbital evolutions of the 39 clones show that all are first strongly dominated by close approaches and 20 of them collide with a planet within timescales from a few 10^4 yr to several Myr. Half of the clones reach their sink within 8.3 Myr. Interestingly, this timescale is similar to the median lifetime of the observed NEO population (Gladman et al., 2000). However, our sample is too limited to interpret it as the most likely lifetime of Itokawa. Its determination based on the “mortality” of individual clones would require a much larger sample that is still beyond our capabilities with the chosen integrator.

The analysis of the individual evolutions shows nonetheless some possible orbital behaviors of Itokawa during its future evolution. The high frequency of close approaches (essentially to Earth and Venus) is undergone by all clones and causes drastic orbital changes. Consequently, a wide region of the orbital space can be visited and some clones eventually collide with the Earth. Fig. 1 shows two such cases. These examples demonstrate that actual collisions are recorded during the numerical integrations. The clones that do not collide with a planet remain affected by close approaches until they reach a region where some powerful secular or mean motion resonances cause a fast eccentricity increase which sends them into the Sun or outside Saturn’s orbit.

Since each evolution provides only a possible one of Itokawa, one cannot estimate the future pathway of Itokawa’s orbit based on these individual evolutions. However, assuming that taken as a whole they may indicate all the possible regions of the orbital parameter space that Itokawa will visit, we can determine its most likely future pathway. We can thus compute the amount of time spent by all clones in different cells of the orbital space during their evolutions. Starting from the initial location of a clone, we compute the time it spends (in Myr) in different cells of (semimajor axis a , eccentricity e , inclination i) over its whole evolution. We then repeat this computation for all the clones and in each cell, we finally divide the total residence time by the total number of clones. The result can be interpreted as the average residence time of Itokawa in different regions during its future evolution. Here only the 35 clones whose lifetimes are smaller than the total integration time are considered. Fig. 2 shows that the greatest amount of time may be spent entirely inside the Earth’s orbit. Indeed, once on such orbit, no dangerous mechanism but close approaches can destabilize the object. Unless a deep close encounter or an impact occurs, it can remain there over a long timescale as a so-called IEO (inner Earth object; Michel et al., 2000).

4. Collision probability

We observed about 10% of Earth collisions in our numerical integrations. However, because it is a rare event,

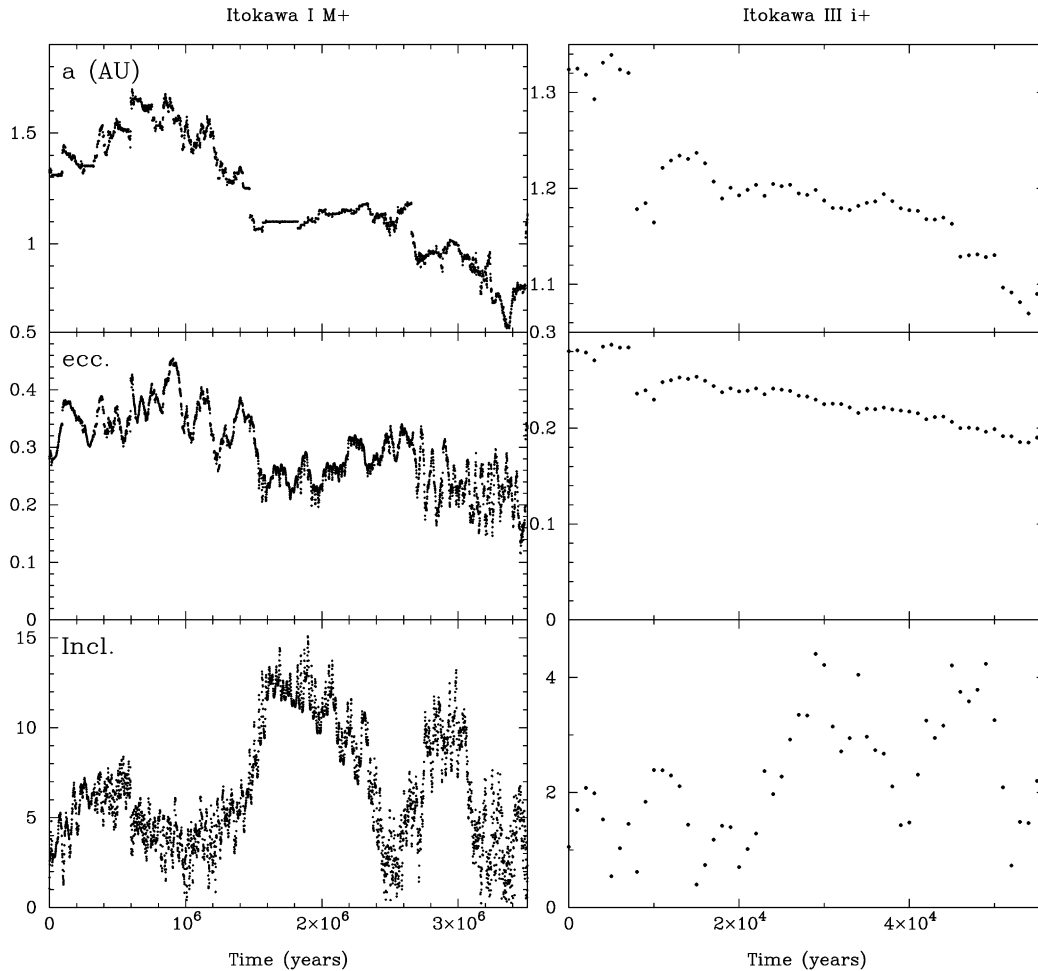


Fig. 1. Evolutions of the orbital elements of two Itokawa's clones until they collide with the Earth. From top to bottom, each set of panels (left and right) shows the semimajor axis (in AU), the eccentricity and the inclination (in degrees) versus time. Both clones have frequent close approaches with Venus and the Earth, so that their orbital elements undergo drastic changes until a collision with the Earth occurs within 3.5 Myr for Itokawa *IM+* (left) and after only 0.056 Myr for Itokawa *IIIi+* (right).

recording the collisions that we observe in our simulations is not enough to estimate the actual collision probability of Itokawa with the Earth. To compute this probability and the associated impact velocity, we adopted a different procedure, which has already been applied to study the Earth meteorite delivery (Morbidelli and Gladman, 1998) and the collision hazards caused by the whole population of NEOs (Gladman et al., 2000; Morbidelli et al., 2002).

Given a set of orbital parameters (a , e , i), we compute the collision probability with a planet using an algorithm described by Bottke et al. (1994a, 1994b), which is a refined version of similar models described by Öpik (1951), Wetherill (1967), and Greenberg (1982). The main assumption in this algorithm is that the orbital angles (mean anomaly, argument of perihelion and longitude of node) of both the planet and the small body are random and circulate uniformly. Therefore, it is not valid during resonant phenomena which cause some orbital angles to librate, thus reducing or enhancing the collision probability of the same set of (a , e , i) with uniform orbital angle distributions. This lim-

itation will be discussed later. However, it also takes into account the so-called gravitational focusing factor, which represents the attraction exerted by a planet and enhances the collision probability. For the impact velocity, the unperturbed encounter velocity $v_{\infty}(a, e, i)$ is first computed using formulas given by Bottke et al. (1994a). Then, the impact velocity is computed taking into account the planet's induced gravitational acceleration with the expression: $v_{\text{imp}}(a, e, i) = \sqrt{v_{\infty}(a, e, i)^2 + v_{\text{esc}}^2}$, where v_{esc} is the planet's escape velocity.

To improve our statistics, we assume again that the evolutions of all the clones taken as a whole over their entire lifetimes give a representation of the possible orbital parameters that Itokawa may acquire. To estimate the average collision probability with a planet, we compute for each clone and for each output of (a , e , i) the associated collision probability. This probability is then multiplied by the 10^3 yr output time interval, assuming that the object remains in the same (a , e , i) cell within this time. The sum of these probabilities over the total lifetime of a clone divided by its

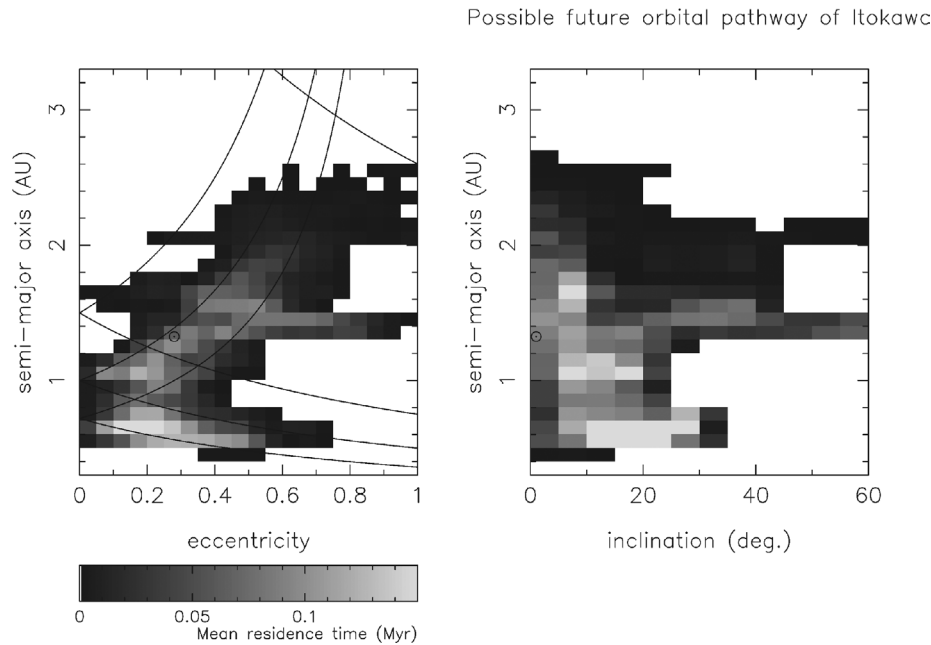


Fig. 2. Mean residence time of Itokawa in different cells of the (a, e) and (a, i) planes during its long term future evolution estimated from the numerical integrations of the 35 clones combined together over their whole lifetime. In the (a, e) plane, the lines represent the planetary-crossing lines (one line for Jupiter and two lines for Mars, Earth, and Venus from top to bottom). The circle with the central dot indicates the actual position of Itokawa's orbit in each plane. A gray scale is used to represent the residence time as shown on the plots. Only the purely white regions are never visited.

lifetime gives its average impact frequency (see Table 1). We repeat this exercise for all the clones. Then, we sum the mean impact frequencies computed for each clone and divide it by the total number of clones. We thus obtain the average impact frequency of Itokawa with the considered planet. The average impact velocity is computed using the same procedure. This algorithm gives results which are consistent with the number of directly observed impacts in the numerical integrations when the latter are also large enough to be statistically reliable (Morbidelli and Gladman, 1998; Gladman et al., 2000). Here, the term frequency is not strictly appropriate because our study concerns an individual asteroid and an impact occurs only one time. Our estimates should rather be interpreted as the timescales over which Itokawa is expected to collide with the respective planets. Table 2 indicates that the expected collisional lifetime of Itokawa with the Earth is about 1 Myr. Since this is the shorter timescale indicated, an Earth impact is the first event expected to stop its evolution.

The computation of these probabilities can be subjected to several sources of errors. In particular, the assumption of a uniform circulation of the orbital angles is not always correct. In a few cases, a clone is trapped in the Kozai resonance, which makes its argument of perihelion librate (e.g., Michel and Thomas, 1996). However, we checked that these events are always very short and never lead to high collision probabilities. Consequently, their contribution is negligible in the average collision probability computed over the object's lifetime. Another more critical problem occurs when the orbital inclinations of both the small body and the planet are identical. In that case, the probability can go to infinity.

To avoid this problem, when such a geometry occurs, the algorithm separates arbitrarily the two inclinations by 0.002° so that a finite value can be obtained. Although it is a real fact that the probability can increase when the mutual inclination is near zero, we checked that when it occurs, the value does not dominate the other ones or cause an artificially high probability.

Our estimate and the actual records of Earth collisions in the integrations make us believe that an impact with the Earth on a timescale of 1 Myr should be considered as a serious possibility. This timescale lets plenty of time to do something about it if necessary, but it is only a factor of four larger than the estimated impact frequency of bodies of this size (Morbidelli et al., 2002; Stuart and Binzel, 2004). This makes Itokawa a good candidate to be among the next potential Earth impactors of this size. Mitigation strategies rely essentially on our knowledge of impactors' physical properties, so the fact that Hayabusa will bring back samples of this object makes it even more interesting.

5. Influence of the Yarkovsky effect

Finally, a non-gravitational force can also contribute to the long term evolution of asteroids in the size range 0.1–20 km. This so-called Yarkovsky effect is a thermal radiation force that causes small bodies to undergo semimajor axis drift, depending on their size, spin, orbit and material properties (see Bottke et al., 2002, for a review). However, the frequent planetary encounters undergone by Itokawa may prevent this force to build up its slow effect. To check this, we

Table 1
Lifetimes, fates, and average Earth impact rates of the 39 Itokawa clones over their whole lifetime

Body	Lifetime (Myr)	Fate	Impact rate (yr ⁻¹)
Itokawa I	7.703	Venus	1.4×10^{-6}
Itokawa Ia+	49.563	Mercury	7.6×10^{-7}
Itokawa Ia-	0.172	Venus	1.5×10^{-6}
Itokawa Ie+	4.214	Ejected	4.0×10^{-7}
Itokawa Ie-	11.560	Sun	8.3×10^{-7}
Itokawa Ii+	6.959	Sun	7.3×10^{-7}
Itokawa Ii-	1.088	Sun	5.3×10^{-7}
Itokawa IΩ+	12.690	Earth	1.8×10^{-6}
Itokawa IΩ-	13.510	Venus	5.6×10^{-7}
Itokawa Iω+	1.817	Sun	2.9×10^{-7}
Itokawa Iω-	27.980	Venus	3.4×10^{-7}
Itokawa IM+	3.510	Earth	1.1×10^{-6}
Itokawa IM-	0.903	Venus	1.7×10^{-6}
Itokawa II	13.345	Venus	1.9×10^{-6}
Itokawa IIa+	57.498	Sun	3.7×10^{-7}
Itokawa IIa-	8.381	Sun	4.6×10^{-7}
Itokawa IIe+	8.782	Venus	1.1×10^{-6}
Itokawa IIe-	>100		
Itokawa III+	43.238	Venus	3.7×10^{-7}
Itokawa III-	1.127	Sun	6.2×10^{-7}
Itokawa IIΩ+	>100		
Itokawa IIΩ-	44.221	Jupiter	1.2×10^{-6}
Itokawa IIω+	6.938	Sun	6.4×10^{-7}
Itokawa IIω-	2.895	Sun	3.4×10^{-7}
Itokawa IIM+	49.254	Sun	7.1×10^{-7}
Itokawa IIM-	>100		
Itokawa III	0.298	Sun	3.7×10^{-7}
Itokawa IIIa+	4.452	Sun	1.5×10^{-6}
Itokawa IIIa-	2.682	Venus	3.2×10^{-7}
Itokawa IIIe+	16.033	Venus	1.4×10^{-6}
Itokawa IIIe-	4.461	Sun	3.9×10^{-7}
Itokawa IIIi+	0.057	Earth	1.6×10^{-6}
Itokawa IIIi-	32.587	Venus	1.5×10^{-7}
Itokawa IIIΩ+	27.605	Venus	1.1×10^{-6}
Itokawa IIIΩ-	36.359	Sun	7.6×10^{-7}
Itokawa IIIω+	3.374	Venus	9.9×10^{-7}
Itokawa IIIω-	31.281	Venus	1.4×10^{-6}
Itokawa IIIM+	>100		
Itokawa IIIM-	4.056	Earth	3.5×10^{-6}

The Earth impact rate is computed with the method explained in Section 4. The first 26 evolutions have been computed with the AMD Athlon computer, using a convergence criterion of either 10^{-12} (label I) or 10^{-8} (label II). The last 13 evolutions have been computed with a Compaq Dec Alpha workstation, using a convergence criterion of 10^{-12} (label III). The other label indicates which orbital parameter has been changed initially from the nominal one (see text for details). In the column end-state, the name of the planet onto which Itokawa collides is indicated, or Sun means a solar collision, and ejection means that the object has been ejected beyond Saturn's orbit. This column and the one indicating the average impact rate are left empty for the 4 clones which lifetimes are greater than the maximum integration time.

integrated numerically 13 of our clone orbits over 100 Myr using an integrator including this effect (Broz, 2002) and based on an algorithm developed by Levison and Duncan (1994). The required physical quantities are either the ones known for the asteroid (Abe and Fujiwara, 2004), or the

Table 2
Average impact frequencies and velocities of Itokawa with the terrestrial planets

	Mercury		Venus		Earth		Mars	
	$\langle F \rangle$	$\langle V_{\text{imp}} \rangle$	$\langle F \rangle$	$\langle V_{\text{imp}} \rangle$	$\langle F \rangle$	$\langle V_{\text{imp}} \rangle$	$\langle F \rangle$	$\langle V_{\text{imp}} \rangle$
BS	1242.8	19.0	33.7	13.4	1.0	13.4	875.7	10.4
Yarko	748.5	25.8	40.7	15.9	0.8	13.7	753.2	14.0

The first line indicates the average impact frequencies $\langle F \rangle$ (in Myr) and impact velocities $\langle V_{\text{imp}} \rangle$ (in km/s) computed from the Bulirsch–Stoer integrations (BS) accounting only for the planetary gravitational perturbations. The evolutions of all clones labeled I, II, and III whose lifetimes are smaller than the integration time have been considered to compute these averaged values. The values computed from the integrations which include the Yarkovsky effect are indicated on the second line (Yarko); the material parameters of Itokawa used in this case were a 500 m effective average diameter, a 2.7 g/cm^3 bulk density, a 0.35 albedo, a 12.132 h retrograde rotation period with the spin axis perpendicular to the orbital plane, and assumed 0.01 W/K/m thermal conductivity, 680 W/kg/K thermal capacity, 0.9 infrared emissivity.

ones usually adopted for S-type asteroids, assuming a thin layer of regolith on its surface (see Table 1). The integrations confirm that the Yarkovsky effect remains undetected due to the strong domination of planetary encounters. Half of the clones reach again their sink within 8 Myr, the dynamical mechanisms that they undergo and their fates are also similar to previous ones. The collision probabilities with planets lead to an expected collision with the Earth on a similar timescale. The other small quantitative differences which suggest a trend toward slightly smaller impact frequencies (Table 1) are not relevant as they do not change the conclusions based on the purely gravitational evolutions.

6. Conclusion

In summary, Itokawa is not a dynamically peculiar asteroid, but its potentially high probability of colliding with the Earth in a Myr is particularly interesting. Other intriguing physical aspects are its high albedo (>0.3) compared to typical albedos of S-type asteroids (0.11–0.22) and its low rotation period (12.1 h). The high-albedo value may be due to crater processes which reveal fresh unweathered surface areas. The low rotation period is more difficult to interpret and may be linked to the collisional history of Itokawa. Its visit by the Hayabusa spacecraft will certainly shed some light on these issues and become of prime interest if its threatening aspect is confirmed. The analysis of Itokawa's samples will have great implications in many fields like the ones aimed at establishing the links between meteorites and asteroids or at characterizing the impact response of small bodies as a function of their physical properties (Michel et al., 2003, 2004). It is then clear that “post-Hayabusa” sample return missions targeted to asteroids with different taxonomic types should be considered of high priority to clarify the physical properties of the whole asteroid population, and in particular the most threatening bodies.

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