*Formation, Detection, and Characterization of Extrasolar Habitable Planets*
*Proceedings IAU Symposium No. 293, 2012*
*N. Haghighipour, ed.*

doi:10.1017/S1743921313012969

# Giant Impacts and Debris Disks

**H. Genda[1], H. Kobayashi[2] and E. Kokubo[3]**

[1]Earth-Life Science Institute, Tokyo Institute of Technology,
2-12-1 Ookayama, Meguro-ku, Tokyo, Japan
email: genda@elsi.jp

[2]Department of Physics, Nagoya University,
Furo-cho, Chikusa-ku, Nagoya, Japan

[3]Division of Theoretical Astronomy, National Astronomical Observatory of Japan,
2-21-1 Osawa, Mitaka, Tokyo, Japan

**Abstract.** During the last stage of terrestrial planet formation, Mars-sized protoplanets often collides with each other. Our high-resolution impact simulations show that such giant impacts produce a significant amount of fragments within the terrestrial planet region. These ejected fragments form a hot debris disk around the central star. We calculated the evolution of the surface density and size distribution of the debris disk using the analytical model of collision disruption, and estimated its infrared excess emission. We found that 24 $\mu m$ flux from the debris disk is higher than stellar flux throughout the giant impact stage ($\sim 10^8$ years), which can explain the infrared excess recently observed around the star with the age of $10^7 - 10^8$ years.

**Keywords.** planets and satellites: formation, hydrodynamics, methods: n-body simulations

## 1. Introduction

The formation process of the terrestrial planets can be divided into three stages; the formation of planetesimals by accretion among dust particles (e.g., Goldreich & Ward 1973; Youdin & Shu 2002), the formation of a few tens of Mars-sized protoplanets through a successive accretion of planetesimals (e.g., Wetherill 1985; Kokubo & Ida 1998), and finally the formation of terrestrial planets by giant impacts among protoplanets (e.g., Chambers & Wetherill 1998; Agnor *et al.* 1999). This final stage is known as the giant impact stage, and lasts $\sim 10^8$ years.

Recently, thanks to infrared space telescopes such as *Spitzer*, several hot debris disks around solar-type stars (FGK) with the age of $10^7 - 10^8$ years have been reported (e.g., Zuckerman *et al.* 2011). From view points of their stellar age and the location of debris disks, the relation between these hot debris disks and giant impact events has recently discussed (e.g., Weinberger *et al.* 2011; Jackson & Wyatt 2011; Melis *et al.* 2012).

Here, we perform high-resolution simulations of giant impacts by considering the impact conditions taken from $N$-body simulations of protoplanets (Kokubo & Genda 2010), and quantitatively estimate the mass of ejected fragments by each giant impact that occurrs during the giant impact stage. We calculate the evolution of the surface density and size distribution of the debris disk using the analytical model of collision disruption (Kobayashi & Tanaka 2010), and estimate its infrared excess emission.

## 2. Giant impact simulations

Using $N$-body simulations, Kokubo & Genda (2010) investigated formation of terrestrial planets from protoplanets. They considered 16 protoplanets ($2.3M_\oplus$ in total) as the initial conditions, and performed 50 runs. In Run1 of Kokubo & Genda (2010), 35 giant

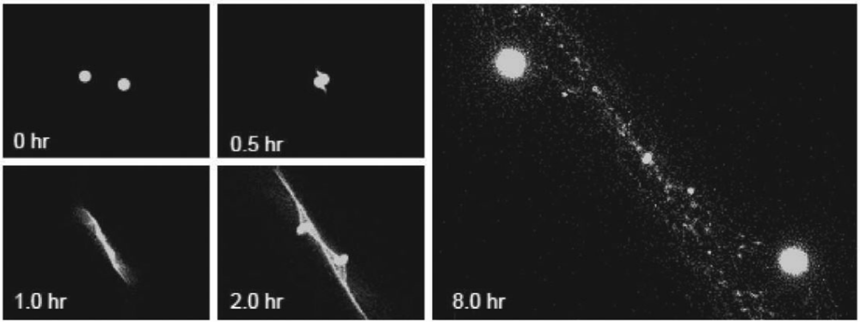


**Figure 1.** Snapshots of simulations for the collision between two protoplanets with the masses of $6.7 \times 10^{23}$ kg and $6.1 \times 10^{23}$ kg. The impact velocity and angle are 9.95 km/s and 16.5 deg, respectively. The impact condition is taken from the 11th collision of Run1 in Kokubo & Genda 2010. A large amount of materials is ejected by the collision, and many clumps are formed.

impacts occur. For all giant impacts in Run 1, we perform high-resolution ($10^5$ particles) impact simulations using the smoothed particle hydrodynamic (SPH) method (Genda *et al.* 2012).

Figure 1 shows snapshots of a giant impact for the 11th collision in Run 1. After the first contact, the protoplanets escape from each other and are no longer gravitationally bound. In this collision, a large amount of fragments ($\sim 1/20 M_\oplus$) is ejected. The mass of the largest clump except for protoplanets is composed of $\sim 2500$ SPH particles, which corresponds to 1/2 lunar mass. From the simulations for 35 sets of giant impacts in Run1, we found that the cumulative mass of ejected fragments becomes $0.4 M_\oplus$, which corresponds to $\sim 20\%$ of the total mass of the protoplanets ($2.3 M_\oplus$). Therefore, the region of terrestrial planet formation should be filled with fragments produced by giant impacts.

## 3. Evolution of a debris disk and its infrared excess

Successive collisions among the ejected fragments produce smaller fragments (i.e., collision cascade). The fragments with sub-micron size are quickly removed by the radiation pressure of the central star. Therefore, the surface density and size distribution of a debris disk decreases and changes with time, relatively. On the other hand, giant impacts supply the fragments to the system. In order to calculate the evolution of the surface density and size distribution of the debris disk, we use the analytical model of collision disruption. According to Kobayashi & Tanaka (2010), the mass depletion time for a debris disk ($\tau_{\rm dep}$) is estimated as

$$\tau_{\rm dep} = 4.2 \times 10^6 \left(\frac{m_{\rm lrg}}{6 \times 10^{22}\,{\rm kg}}\right)^{0.64} \left(\frac{a}{1{\rm AU}}\right)^{4.18} \left(\frac{\Delta a/a}{0.1}\right) \left(\frac{e}{0.1}\right)^{-1.4} \left(\frac{M_{\rm frg}}{6 \times 10^{23}\,{\rm kg}}\right)^{-1} \text{years},$$

where $m_{\rm lrg}$ and $M_{\rm frg}$ are the mass of the largest fragments and the total mass of the fragments in the ring-like debris disk with the width $\Delta a$ and eccentricity $e$ at the distance $a$ from the central star. In the previous section, we have obtained the time and location (i.e., $a$) that giant impacts occur, and the mass of the ejected fragments ($M_{\rm frg}$) and largest clump ($m_{\rm lrg}$) produced by each giant impacts. Typical depletion time for a debris disk produced by single giant impact is about $10^6 - 10^7$ years, when we assume $\Delta a/a = 0.1$ and $e = 0.1$.

Figure 2 shows the time evolution of $24\mu m$ flux calculated by the analytical model of collision disruption. We assume that the giant impact stage begins with $10^7$ years. As

https://doi.org/10.1017/S1743921313012969 Published online by Cambridge University Press

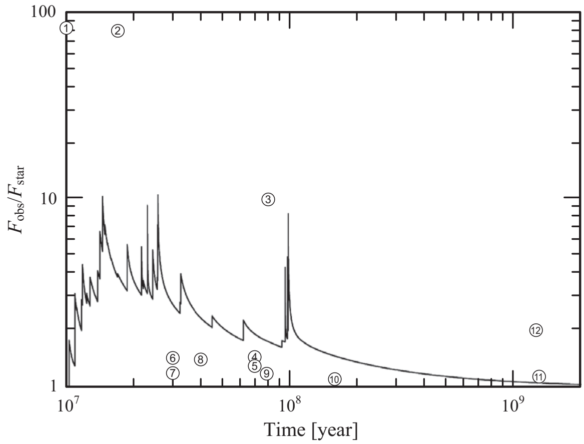


**Figure 2.** The ratio of $24\mu m$ observed flux ($F_{\rm obs}$) to $24\mu m$ stellar flux ($F_{\rm star}$) against the stellar age. The observed flux ($F_{\rm obs}$) is the sum of $F_{\rm star}$ and $F_{\rm deb}$ (flux from debris disk). The solid line represents the numerically calculated flux ratio during the giant impact stage. The circled numbers represents the observed flux ratio of solar-type (FGK) stars with hot debris disk; (1) HD 145263, (2) HD113766, (3) HD 15407, (4) HD 19668, (5) HD 118008, (6) HD 12039, (7) HD 43989, (8) HD 84075, (9) HE 750, (10) HD 90905, (11) HD 40136, and (12) HD 109085. Data are taken from (1-2) Chen *et al.* (2011), (3) Melis *et al.* (2010), (4-8) Zuckerman *et al.* (2011), (9-10) Carpenter *et al.* (2009), and (11-12) Beichman *et al.* (2006).

seen in this figure, there are many spikes of $24\mu m$ flux, which correspond to each giant impact events. We can find that 24 $\mu m$ flux from the disk is higher than stellar flux throughout the giant impact stage ($\sim 10^8$ years), which can explain the infrared excess recently observed around the star with the age of $10^7 - 10^8$ years.

## References

Agnor, C. B., Canup, R. M., & Levison, H. F. 1999, *Icarus*, 37, 219
Beichman, C. A., Bryden, G., Stapelfeldt, K. R., *et al.* 2006, *ApJ*, 652, 1674-1693
Chambers, J. E. & Wetherill, G. W. 1998, *Icarus*, 136, 304
Carpenter, J. M., Bouwman, J., Mamajek, E. E., *et al.* 2009, *ApJS*, 181, 197-226
Chen, C. H., Mamajek, E. E., Bitner, M. A., Pecaut, M., Su, K. Y. L., & Weinberger, A. J. 2011, *ApJ*, 738, 122
Genda, H., Kokubo, E., & Ida, S. 2012, *ApJ*, 744, 137
Goldreich, P. & Ward, W. R. 1973, *ApJ*, 183, 1051
Jackson, A. P. & Wyatt, M. C. 2012, *MNRAS*, 425, 657-679
Kobayashi, H. & Tanaka, H. 2010, *Icarus*, 206, 735-746
Kokubo, E. & Genda, H. 2010, *ApJL*, 168, 433
Kokubo, E. & Ida, S. 1998, *Icarus*, 131, 171
Melis, C., Zuckerman, B., Rhee, J. H., & Song, I. 2010, *ApJL*, 717, L57-L61
Melis, C., Zuckerman, B., Rhee, J. H., *et al.* 2012, *Nature*, 487, 74-76
Weinberger, A. J., Becklin, E. E., Song, I., & Zuckerman, B. 2011, *ApJ*, 726, 72
Wetherill, G. W. 1985, *Science*, 228, 877
Youdin, A. N. & Shu, F. H. 2002, *ApJ*, 580, 494
Zuckerman, B., Rhee, J. H., Song, I., & Bessell, M. S. 2011, *ApJ*, 732, 61