Experimental Simulation of Collisions

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1. Introduction

According to the current scenarios of the planetary formation, it is believed that the planets and satellites have grown from planetesimals through destruction and accretion events by mutual collisions among planetesimals. The evidence for these processes is observed in the cratered planetary surfaces and irregular shape of the minor satellites and asteroids. Collisional evolution of the protoplanetary bodies or asteroids has been numerically simulated using large computers in the past decade (e.g., Greenberg et al., 1978; Hayakawa et al., 1989). For these simulations, usually adopted pictures are as following; Many solid bodies moving in individual Keplerian orbits around a central massive body mutually collide many times. In every collision, between the two bodies, they are eroded or destroyed depending on the collisional velocity and the size of the bodies, and at the same time, many fragmental bodies are produced. One group of the fragments having a velocity lower than the escape velocity of the body are retained, while the others escape from the body. The bodies which have grown large enough to capture most of the impacting mass can increase their mass rapidly.

In considering these processes, the most important elementary process is the collision between two solid bodies. The fundamental quantities needed in the study of a collisionally evolving system are the size and velocity
distribution of the fragments produced in the collision, that is, we must know the number of fragments of any mass and velocity. Moreover, it is necessary to know, in the collision of the planetary or planetesimal size of bodies, how these quantities depend on the various parameters such as the size, density, and strength of both the projectile and the target, as well as the collisional velocity. In order to solve these problems, as a first step, small scale impact experiments have been carried out in many laboratories. Based on the obtained data, a few scaling laws intended to be applied to the large scale collisional phenomena in the solar system have been proposed (Mizutani et al., 1990; Housen and Holsapple, 1990).

In laboratory experiments, usually, projectiles of about 1 cm are launched by various types of guns and impacted into larger size targets to investigate the cratering or disruption phenomena. The data bases on these phenomena are growing by extensive works in several laboratories. However, many important works are still left to be done. First, the data on the velocity distribution are still not enough, while considerable number of results on the size distribution exist. Secondly, existing data are most abundant for rocky targets (especially basalt), on the other hand the data on ice targets are only gradually increasing. Moreover, in most experiments, the materials and shapes of the projectiles have not been widely tested (the most common materials are plastics and metals). These situations are very frustrating to establish a scaling law applicable to a wide variety of parameters of cosmic interest. It is most important in this field to get the data of the size and velocity distributions for wide varieties in density and strength of both the targets and projectiles as well as in a wide range of collisional velocities.

In this paper, a few new experimental results toward the above prospects are provided. In the next section, the velocity and its distribution of fragments are presented. Dependence of disruptive properties on the material of projectiles and targets is discussed in section 3. In the last section a short summary and future prospects are described.

2. Velocity and its distribution of the fragments

When a projectile strikes onto a solid body, a nearly-spherical strong shock wave forms from the impacted site. The stress in the shock wave is strong enough to produce cratering and various type of metamorphisms
depending on the impact velocity. In the first stage of the cratering, very fine ejecta, called jet, are splashed out from the impacted site due to the strong pressure gradient induced near the site. The highest velocities of these ejecta from basalt targets impacted by aluminum projectiles of 6km/s velocity are reported to exceed 10km/s, although their mass fraction is very small (Gault and Heitowit, 1963). These may include melted materials or vapors if the induced shock wave is strong enough. In the following stage (excavation stage), most of the masses in the cratering are thrown out in moderate velocities. Information on the velocity distribution of the fragments in cratering is strongly required by many planetary scientists, but the data sources are quite restricted due to the difficulty of the work. Gault and Heitowit (1963) determined the velocity distribution in cratering on basalt plane surfaces impacted by high-velocity aluminum spheres and found that the cumulative mass ejected at a velocity higher than \( v \) is roughly expressed by \( v^{-2.5} \), although a knee was found at about 1km/s in the distribution.

In the stage following cratering, the shock wave whose stress is sufficiently attenuated, propagates deeply into the target, and then reflects as a tensile wave, on the backside or lateral free surfaces of the target. If the target size is small enough, the reflected wave has a tensile stress enough to spall the surface layers (Rinehart, 1960). As a result, the spalled fragments carry away part of the momentum contained in the wave. The tensile wave, if it still has enough energy, can produce the second, third, and multiple spallations, successively from the surface toward the interior of the target. When the tensile wave retained in the target attenuates sufficiently, lower than the tensile strength of the target material, the spalling ceases, leaving the central part of the target (called as core) intact. The size of the finally left core depends on the strength of the reflected wave.

In this type of collision (hereafter we call this catastrophic disruption or CD), the velocity distribution of the fragments for the whole size range has not yet been obtained. However, a part of them were obtained recently using high-speed cameras and an image analyzer, although it is still only for restricted parameter sets. The velocity distribution for the fragments produced in the CD of an alumina ceramic sphere and a basalt sphere by the impact of projectiles 7mm in diameter and a 3-4km/s velocity was determined (Nakamura and Fujiwara, 1989; 1991). The velocity vector field of the fragments for the basalt spherical target is shown in Fig. 1. It is
noted that, in spite of the oblique impact, the velocity field was almost symmetrical about the surface normal vector at the impacted site as noted in an earlier work (Fujiwara and Tsukamoto, 1980). The velocity vector of the fragments systematically changes; it is highest near the impacted site, and decreases toward the antipode as long as the surface fragments are concerned. The core fragment has the lowest velocity. For the alumina target, at the antipode of the target, the fragment velocity is much higher than the velocity at the nearby neighbors, which is also reported for the impact into glass targets (Gault and Wedekind, 1969). This may occur due to the focusing of the wave reflected on the surface of the spherical target (Rinehart, 1960). This effect seems to appear clearly from the targets made from uniform materials. The velocity field for basalt was proposed by a simplified semiempirical formula (Paolicchi et al., 1989). This is acceptable in a very rough approximation except for the fragments neighboring the impact point.

The two-dimensional and the three-dimensional velocity distributions of the fragments of a size larger than a few mm (these fragments occupy more than 95 percent of the target mass) in the disruption of basalt is shown in Fig. 2. The three-dimensional velocity distribution is approximated by
Fig. 2. 2-D (open points) and 3-D (solid points) velocity distribution of the basalt fragments versus fragment mass normalized by the initial target mass. Fragments coming along the line of sight have low 2-D velocity. The 3-D velocity distribution is determined for the prominent fragments most of which ejected from the target surface.

minus one-sixth of the power of the fragment mass. Similar results were obtained for the alumina sphere. These results mean that the kinetic energy of the individual fragment depends on two-third of the power of the fragment mass, which is the same dependence as the energy expended to make the surface area of the fragment. The kinetic energy for individual fragments is several times higher than the surface energy, and these are one to two orders of magnitude higher than the rotational energy (Fujiwara, 1987). The kinetic energy expended in a bulk of fragments larger than a few mm is about 2 percent of the projectile energy.

We are just standing at the first step to determine systematically the velocity distribution of the fragments. Determining the velocity distribution needs much time-consuming work. A method for a faster disposal of data is strongly desired to get larger amount of the data.
3. The dependence of disruptive properties on the materials of projectiles and targets

It is important to investigate the dependence of the impact process on the materials of projectiles and targets in order to apply the laboratory data to the natural phenomena in the early solar system. Many experimental investigations have been performed in rocks and sands. Some experimental data have also been reported on ice targets (Lange and Ahrens, 1981; Kawakami et al., 1983; Cintala et al. 1985; Lange and Ahrens, 1987). However, these impact experiments on ice are insufficient to study the dependence of projectile materials and to inform the detailed mass distribution of ice fragments. Recently Kato et al. (1991) carried out impact experiments on ice, including the use of water ice projectiles in a low temperature laboratory of the Institute of Low Temperature Science, Hokkaido University. In this section, the experimental results on these ice impacts are briefly summarized and compared with the data on rocks and ices obtained in previous studies. The details on ice experiment are referred to Kato et al. (1991).

Water ice projectiles, 15mm in diameter, 10mm in length, and 1.7g of mass were struck on an ice target under a temperature of $-18^\circ$C, while aluminum (5g) and polycarbonate (2g) projectiles with the same dimensions were used under the same temperature for comparison. Two types of polycrystalline ice targets were examined to check the effects of grain size and crystal orientation: commercially produced blocks consisting of elongated megacrystals of some centimeters, and the ice blocks freezed at $-18^\circ$C, obtained from a mixture of snow powders, with a size of 1mm, and cooled water. Microscopic observation showed the homogeneous distribution of tiny crystals with little crystal growth for the latter ice blocks. The dimensions of the targets used were about 30cm for cratering experiments and about 10cm for fragmentation. The projectiles were accelerated by high pressure gas of N$_2$, and the impact velocity ranged from 60 to 400m/s. Under these conditions of velocity and temperature, neither the projectiles nor targets experienced a melting state due to insufficient temperature elevation in the shock release.

Cratering experiments

Morphological changes in the crater, from a tabular plateau to a pit
type or bowl shape, with increasing impact velocity evidently appeared in a quite narrow velocity range of impact with ice and aluminum projectiles. Moreover, the dependence of the crater shape on the projectile materials was very large; double craters with a central pit were formed over about 300 m/s with the use of ice projectiles, while bowl shaped craters were produced above 230 m/s with aluminum projectiles. Polycarbonate projectiles only produced the tabular plateau type of crater in these experimental conditions. Plate-like fragments suggesting the spallation of the impacted surface were recovered in all the runs. In low velocity impacts, where shallow flat craters were made, the ejecta were easily fit back into the cavity. Although the measured crater diameters are possibly put on a single regression line in a power-law of kinetic energy with an exponent of 0.54, it is better to fit these into the regressions with an inflection in the vicinity of 70 J (Fig. 3), considering the data for crater volume. The power-law exponent obtained had almost the same value of 0.3 for ice, aluminum, and polycarbonate projectiles in the low energy range. This value is consistent with that reported by Lange and Ahrens (1987), within the experimental error, where the power-law exponent was estimated to be 0.38 with the use

![Graph showing the dependence of crater diameter on kinetic energy for ice craters impacted by ice, aluminum, and polycarbonate projectiles. The data for confined and unconfined ice at 257 K from Lange and Ahrens (1987) are shown by dashed lines.](image)

Fig. 3. Dependence of diameter on the projectile kinetic energy for ice crater impacted by ice, aluminum and polycarbonate projectiles. For comparison, the data for confined and unconfined ice at 257 K from Lange and Ahrens (1987) are shown by dashed lines.
of polycarbonate projectiles and the unconfined ice targets at 257 K. In the high energy impacts, the exponents were increased to 1.0 for ice and 0.8 for the aluminum and polycarbonate projectiles resulting in a higher cratering efficiency in ice impact than in non-ice projectiles. The inflected regression lines were also obtained in the logarithmic expression of late-stage effective energy (Mizutani et al., 1983), multiplied impact pressure by projectile volume. Almost the same exponents of 0.56 for ice, polycarbonate, and aluminum projectiles in the range lower than 400 Joules of energy were consistent with the data by Lange and Ahrens (1987), although these exponents were larger than the results obtained in Kawakami et al. (1983).

The shape of the crater, as mentioned above, was largely altered depending on the projectile material and impact velocity, so the dimensional comparison in depth as carried out by Mizutani et al. (1983) is inadequate. Hence, crater volumes were plotted in the logarithmic form of kinetic energy of the projectile as well as of the late-stage effective energy (Fig. 4). In these cases, we obtained inflected regression lines for each projectile material, which concurrently with the plot of crater diameter vs. energy, suggests the crater volume dependence on the material and energy of the projectile. In the range of low energy, the crater produced by ice projectiles was smaller than that produced by aluminum and polycarbonate projectiles by a factor of 0.6 to 0.8, while the high-energy impact of ice to ice engulfed a larger volume of craters than other materials. Inflections in both ice, aluminum, and polycarbonate projectiles occurred at almost the same energy range of 70 Joules and impact pressure of 200MPa. A least-squares fit gives the slope of 0.90 to 0.95 for the three kinds of projectiles in the low pressure range, which are close to the values for confined ice targets of Lange and Ahrens (1987) and for basalt of Moore et al. (1963). No remarkable differences in crater volume and diameter between the two types of ice targets were observed as shown in Figs. 3 and 4. However, the length of radial cracks extended over the crater rim in the commercial ice blocks were larger by 1.5 times than in the ones produced in the laboratory.

As well as the diameter of ice crater, the power-law exponents of volume in the high impact energy range were also larger than in other target materials such as water, sands, and competent rocks (Schmidt, 1980; Schmidt and Housen, 1987). Although a large deviation of power-law indices from non-ice targets, especially for strength-dominated rocks, has never been ex-
plained in either experimental or numerical studies, some reasons can be supposed: the higher values in generated impact pressures, compared to the material strength even in the low velocity range of this study. The peak pressure generated by an impact of 400m/s was estimated to be 330MPa by the planer impact approximation (Melosh, 1989), while the tensile strength for the spallation of impact surface was reported at only 18MPa (Lange and Ahrens, 1983). The compressional strength controlling the degree of volume crushing below the surface was estimated at about 100MPa in the high strain range from a yield strength of 30MPa in the low strain deformation (Durham et al., 1983). A smaller strength of ice probably results in the crater volume with 1.5 orders of magnitude larger than in competent rocks such as basalt and gabbro (Lange et al., 1984), which have a tensile strength of about 150MPa.
Fragmentation experiment

A large difference was observed between the energy required to initiate the fragmentation by the impact of ice and aluminum projectiles: 0.08 J/g for ice and 0.02 J/g for aluminum in the scale of energy density, that is, projectile kinetic energy normalized by target mass. Lange and Ahrens (1981) reported 0.03 J/g of energy density for polycarbonate projectiles at 257 K, which is an intermediate energy value of our data. This dependence of fragmentation on projectile materials and the relation of projectile material and cratering efficiency in the low impact energy, as shown in Fig. 4, imply that the fragmentation initiates by cratering. For ice projectiles the fragmentation proceeded at around 0.1 J/g with high efficiency, as represented in Fig. 5, where the largest fragment mass normalized by the initial target mass was plotted to energy density. The data from aluminum projectiles can be fitted in a straight line different from that in the case of polycarbonate (Lange and Ahrens, 1981) and ice projectiles. The value of the slope is almost the same as in the impact fragmentation of basalt targets previously obtained by Fujiwara et al. (1977), Matsui et al. (1982), and Takagi et al.

![Diagram](image-url)

Fig. 5. Relation of normalized mass of largest fragment with energy density (projectile kinetic energy divided by target mass) in impact fragmentation of ice. The data for 257 K ice (Lange and Ahrens, 1981) and basalt (Fujiwara et al., 1977; Matsui et al., 1982; Takagi et al., 1984) are represented by solid lines.
(1984). The data from Kawakami et al. (1983), which indicates the beginning of fragmentation at a lower range of energy density, deviated from that of Lange and Ahrens (1981) and Kato et al. (1990). This inconsistency probably originated from a difference in the physical conditions of the ice target, especially in the temperature of ice targets. The usefulness of nondimensional impact stress $P_I$ (Takagi et al., 1984; Mizutani et al., 1990) as a scaling parameter is represented in Fig. 6, where the normalized mass of the largest fragment is plotted to $P_I$. Although there exists a large difference in strength between the ice and rocks in addition to the difference in experimental conditions such as target size and impact energy, fragmentation started in the narrow range of $P_I$. However, the values of the slope depend on the target material as well as on the material properties of projectiles. This fact suggests the necessity of more careful consideration concerning the applicability of nondimensional impact stress to ductile materials, even when this parameter does include the physical parameters of projectile and target, density, size, and strength.

One of the purposes of installing the experimental device in the low

![Graph](image-url)  

Fig. 6. Normalized mass of largest fragment to nondimensional impact stress in ice fragmentation. Dotted and dashed lines indicate the data for impact fragmentation of pyrophyllite (Takagi et al., 1984) and basalt (Fujiwara et al., 1977; Matsui et al., 1983; Takagi et al., 1984).
temperature laboratory was to recover the ice fragment without any melting. Hand picking and sieve analysis made possible the determination of mass distribution of a total number of $10^6$ fragments to the smallest size of $10^{-4}$ grams in the total destruction. When the cumulative number $N$ vs. fragment mass $m$ is plotted in a log–log coordinate, the slope providing a measure of the degree of comminution of the target is compared with rocks such as basalt and pyrophyllite. The dependence of the mass distribution of ice fragments on projectile materials was not so large as in the largest fragment mass larger than $10^{-1}$ initial mass as shown in Figs. 5 and 6. However, the slope in log $N$–log $m$ curves significantly depended on target materials: $-0.9$ for ice target (Kato et al., 1991), $-0.44$ to $-0.5$ for basalt (Fujiwara et al., 1977; Takagi et al., 1984), and $-0.6$ for pyrophyllite (Takagi et al., 1984) in the fine fragment region in disruption stage with the largest fragment of mass smaller than 0.3 initial mass. This comparison implies that the ice target was broken to smaller pieces than basalt and pyrophyllite due to the weakness of target, although the same degree of disruption occurred for ice at impact energy and nondimensional impact stress lower than $10^{-1}$ of those for basalt and pyrophyllite.

Impact data of ice well compared with that of rocks and sands was obtained in both the cratering and fragmentation. An extension of the impact condition is required to investigate the inflections in Figs. 3 and 4. In order to refine the scaling law, low temperature impact experiments as tried by Lange and Ahrens (1981) are inevitable.

4. **Summary and future works**

The experimental simulations in laboratory have advanced in studying the velocity distribution of fragments and the dependence of disruptive properties on the materials of targets and projectiles. However, the investigation on kinetic energy partitioning must be extended to a wider range in the collisional mode and impact velocity. Recently Takagi et al. (1990) made new experiments to investigate the partitioning and velocity distribution in a velocity range lower than that of Nakamura and Fujiwara (1989: 1991). Their analyses are still preliminary but suggest that the partitioning rate into the kinetic energy of fragments is higher than that in the high velocity range. Complementary research in high and low velocity ranges will
enlighten this problem.

The experiments on ice suggested that some refinement of the scaling laws are necessary to apply them to ductile materials. Other modifications for porous materials will be required. Further experiments on these materials will refine the scaling law. Experimental methods are, however, restricted to investigate the size dependence of material strength suggested by Housen and Holsapple (1990) and the velocity dependence of the scaling law in a very high velocity range. The combination of the experimental methods and theoretical research with astronomical observations is useful in the solution of these problems (Fujiwara and Takagi, 1988). Studies on the origin of asteroid families (Takagi and Mizutani, 1990) showed the possibility of this combination, where they suggested that the nondimensional impact stress parameter is applicable in high velocity range \((v \approx 10\text{km/s})\) and that the strength of parent bodies of asteroid families is the same as that of some meteorites. Anyway, further collaborations from the investigators studying the collisional phenomena in different size and velocity ranges with different methods are still necessary.

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**References**


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