THE SHAPE OF METEORITES

Hiroichi HASEGAWA

Department of Physics, Faculty of Science, Kyoto University, Kitashirakawa, Sakyo-ku, Kyoto 606

Abstract: The shape of meteorites is described by axial ratio (b/a), where a and b are the longest and the intermediate axial lengths of meteorite, respectively. Used samples are the Yamato meteorites recovered in 1973–1975. Distribution of (b/a) and the average value $\langle b/a \rangle$ of 0.730 of 930 chondrites except carbonaceous ones are obtained. The results are similar to those of basalt fragments in laboratory impact experiment.

Five chondrite showers are also analyzed. Their mass spectra are well represented by power function of fragment mass with the exponents α of 0.95 ± 0.05, 0.60 ± 0.05, 3.0 ± 0.4, 2.5 ± 0.1 and 3.5 ± 0.3. With the assumptions that each shower originated in a single impact, the produced fragments are not lost and the high velocity impact law found by laboratory experiment is applicable to meteorite showers, these showers are of the "core type" destruction with impact energies per unit target mass of 10^7 erg/g–10^8 erg/g. Distributions of (b/a) and the average values $\langle b/a \rangle$ of each shower resemble each other and also those of all chondrites. Among about 40 achondrites, 29 diogenites belong to one shower with rounded fragment ($\langle b/a \rangle = 0.794$) and flat mass spectrum ($\alpha = 0.35 \pm 0.02$).

1. Introduction

Various types of high velocity impact phenomena occur in space. The law of the high velocity impact phenomena was clarified systematically in laboratory experiment by FUJIWARA *et al.* (1977). The types of destruction are classified into the following four stages; crater formation, transient type, core formation and complete destruction according as the increasing impact energy E. The ratio of the maximum fragment mass M_a to the target mass M_t is represented by a descending power function of (E/M_t). The shape, mass spectrum, velocity and rotation speed of fragments are also known. In their experiment, however, target masses of basalt were less than 3 kg and the masses of most fragments analyzed were less than 1 g.

For larger bodies the high velocity impact law could be found from the analysis of destruction phenomena of meteorites occurring in nature. For this purpose, the ensemble of meteorites of the good quality is needed. Discovery of the Yamato meteorites made the analysis possible. It is because the Yamato meteorites were found on the Antarctic ice without the contamination of terrestrial rocks and were recovered by scientists carefully.

In this paper data of about 1000 Yamato meteorites of 1973–1975 collections, published in 1979 as Catalog of Yamato Meteorites (YANAI, 1979), are used. The shape of meteorites is described quantitatively. Fragment mass distributions of 6 meteorite showers are presented. The results are compared with those obtained by laboratory experiment.

2. Shape of Meteorites

The shape of meteorites would reflect the nature of high velocity impact process which they suffered. A method to describe the fragment shape quantitatively was proposed by FUJIWARA *et al.* (1978), the shape being specified by the axial ratios (b/a) and (c/a) where a, b and c are the longest, intermediate and the shortest axial lengths, respectively. Their method is also applied to ice fragments by LANGER and AHRENS (1981).

In the present Catalog, the longest axial length a and the intermediate axial length b are described for most of the meteorites. Distribution of the axial ratio (b/a) of all the chondrites except carbonaceous ones is shown in Fig. 1a, the total number of chondrites being 930. There is a broad maximum over the range from $(b/a)=0.6$ to 0.9. There are no chondrites with $(b/a)<0.3$, *i.e.* the thin rod-shaped chondrites. The average axial ratio $\langle b/a \rangle$ is 0.730. Any tendencies in $\langle b/a \rangle$ which depend on the fragmental mass were not seen. The values of $\langle b/a \rangle$ are 0.745, 0.731, 0.714, 0.707 and 0.721 for the fragmental mass ranges of 1.0–1.9 g, 2–2.9 g, 3–3.9 g, 4–5.9 g and >6 g, respectively.

Our results will be compared with those for the basalt fragments in laboratory ex-

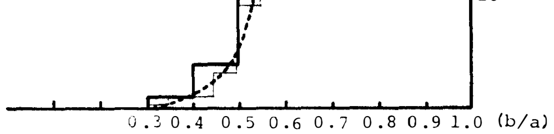

Fig. 1a. Distributions of axial ratio (b/a) for all the Yamato chondrites except carbonaceous ones and for the basaltic fragments of FUJIWARA et al.'s experiment.

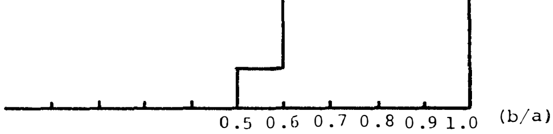

Fig. 1b. Distribution of axial ratio (b/a) for diogenite fragments.

periment (FUJIWARA *et al.*, 1978). In their experiment, the average axial ratios $\langle b/a \rangle$= 0.73 and $\langle c/a \rangle$=0.50 and any fragments with $(c/a)<0.30$ were not found. The latter means the lack of needle-shaped or thin plate fragments. Thin line in Fig. 1a is (b/a) distribution of basalt fragments read from their Fig. 1. The less broad maximum compared with one for chondrite fragments (thick line) is found between (b/a)=0.6 and 0.8. The dashed curve is the smoothed out distribution. Thus, the shape of the chondrites seems to be similar to the shape of the basalt fragments produced by high velocity impact.

3. Characterization of Showers

Among the Yamato meteorites in the Catalog, 5 showers of chondrite and 1 shower of diogenite were assigned (YANAI, 1979). The "shower" means a group of meteorites which is found in a confined area and is recognized by the collector as fragments originated in a single meteorite because of their similar character. In the Catalog the shower is described as, for example, "Yamato-74194 to -74342 are very similar." If so, each shower may keep well the products of destruction of a single target.

Table 1 shows the data on showers. Analysis was made on the assumptions that each shower is produced through a single destruction process and the fragments produced were not lost except fine ones. The law of high velocity impact phenomena found in laboratory experiment was also used.

For each of the five chondrite showers, the maximum fragment mass is considerably larger than the other fragment masses, so the events seem to be of the "core type" destruction. The ratio of the maximum fragment mass M_a to the target mass M_t is related to the impact energy E per unit target mass (E/M_t) by

Table 1. Characterization of showers.

Shower No.	Number of fragments	Total mass M_t(g)	Mass of max. fragment M_a(g)	M_a/M_t (%)	Equivalent* E/M_t (erg/g)	Exponent of mass spectrum α	Shape factor $\langle b/a \rangle$
1	149	715.9	25.9	3.6	6.2×10^7	3.5 ± 0.3 (5–15g)	0.725
4-L	57	110.8	8.1	7.3	3.5×10^7	2.5 ± 0.1 (2.5–8g)	0.738
2-L	38	64.2	6.3	9.8	2.8×10^7	3.0 ± 0.4 (2–4g)	0.702
5-L	150	3919.5	706.9	18.0	1.7×10^7	0.60 ± 0.05 (2–100g)	0.739
3-H	169	5273.8	1719.7	32.6	1.05×10^7	0.95 ± 0.05** (8–100g)	0.739
D1	29	6775.9	2193.9	32.4	1.06×10^7	0.35 ± 0.02 (2.5–700g)	0.794

* Estimated by FUJIWARA's empirical formula, $(M_a/M_t)=1.66 \times 10^8 (E/M_t)^{-1.24}$.
** In the fragment mass range between 80 g to 300 g, $\alpha=1.4 \pm 0.1$.

$$\frac{M_a}{M_t}=1.66\times 10^8(E/M_t)^{-1.24}\,, \tag{1}$$

in the laboratory experiment, where (E/M_t) is measured in erg/g (FUJIWARA *et al.*, 1977). By the use of this empirical formula, the (E/M_t)'s of showers were estimated to be in the range of 10^7 erg/g–10^8 erg/g. In the following the (E/M_t) values estimated by eq. (1) are called the equivalent (E/M_t), because of the difference between the impact-producing agent in laboratory experiment (tiny projectile) and that in meteorite showers (atmospheric impulse).

The shape of fragments in each shower is presented in Fig. 2. Distributions of axial ratio (b/a) resemble each other and also the distribution of all the chondrites except carbonaceous ones shown in Fig. 1a.

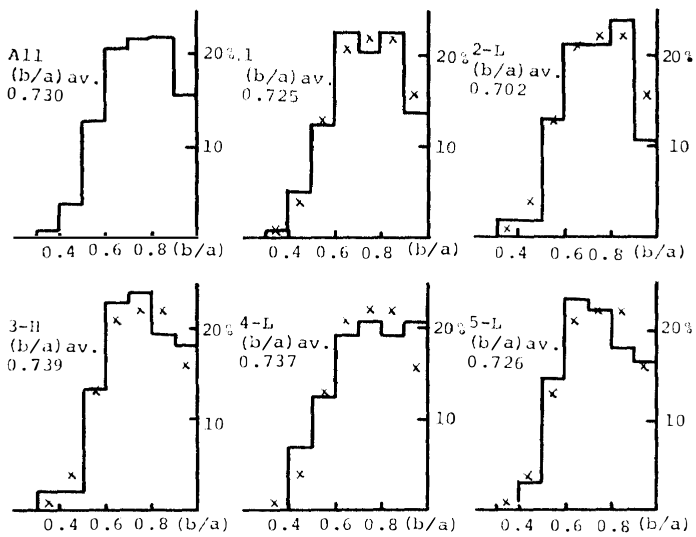

Fig. 2. Distributions of axial ratio (b/a) for all the Yamato chondrites except carbonaceous ones and for 5 chondrite showers. The × in the figures for showers represent the value for all the chondrites except carbonaceous ones.

The integral mass spectrum (cumulative number) for each shower is shown in Fig. 3. Flatness of the spectrum at small masses may be due to the loss of the fine particles. At larger masses the irregularity appears due to the smallness of fragment number. In the intermediate mass, the cumulative number $N(>m)$ of shower is represented well by a power law of mass m as

$$N(>m)\backsim m^{-\alpha}\,. \tag{2}$$

For the showers 3-H an 5-L, differential mass spectra were found to be represented by power law as well, the exponent being to be $-(\alpha+1)$. The exponents of differential mass spectra are 2.02 ± 0.26 for shower 3-H and 1.64 ± 0.18 for shower

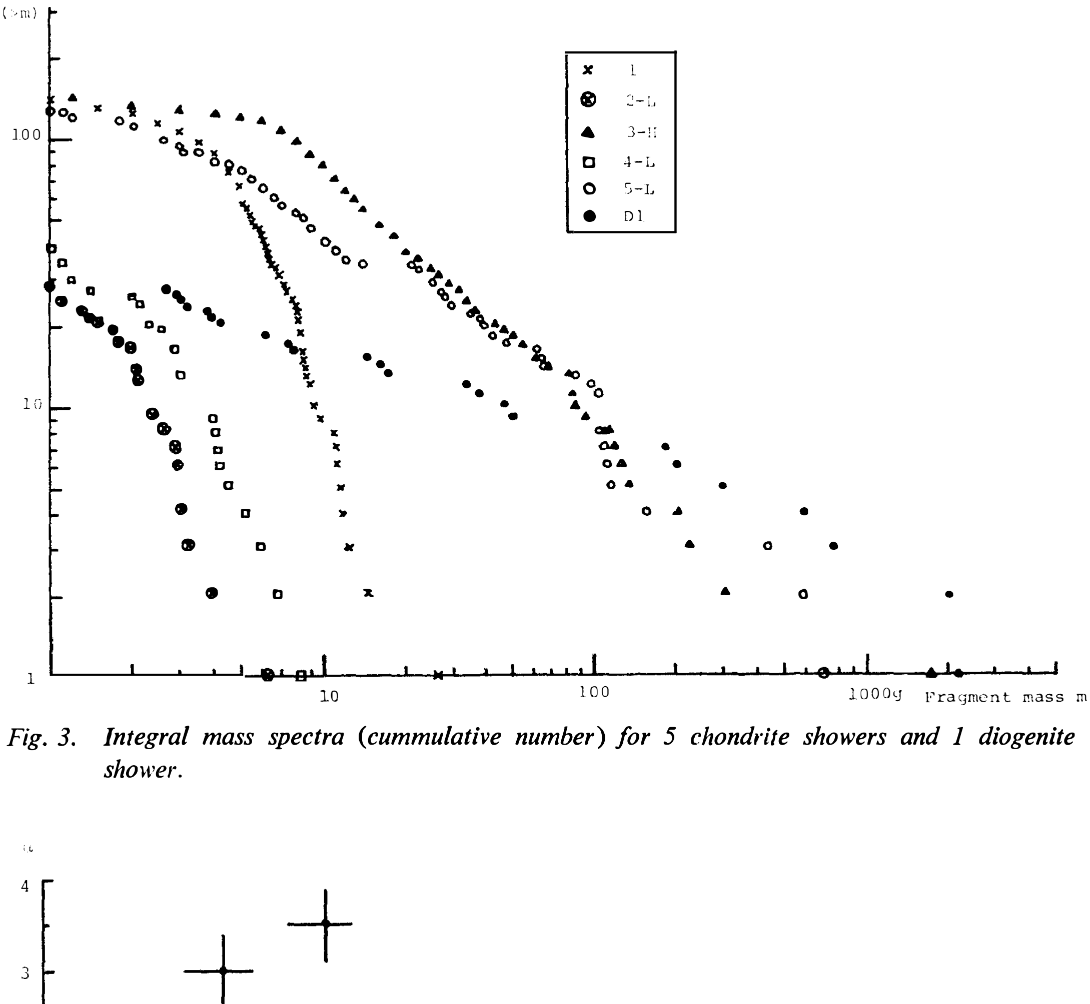

Fig. 3. Integral mass spectra (cummulative number) for 5 chondrite showers and 1 diogenite shower.

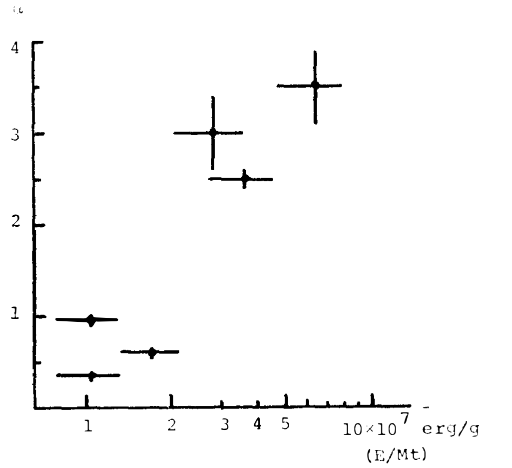

Fig. 4. Equivalent (E/M_t) vs. exponent α of mass spectrum for showers, errors in (E/M_t) being taken as $\pm 20\%$.

5-L, which are consistent with those of the integral mass spectra (0.95 ± 0.05 for 3-H and 0.60 ± 0.05 for 5-L). For the other three showers, the exponents are very large ($\alpha > 2$), and equivalent (E/M_t)'s are larger than those for the two showers 3-H and 5-L. In Fig. 4 exponent and equivalent (E/M_t) are plotted, the error in (E/M_t) is taken as $\pm 20\%$.

Some care is needed in comparing the present results with those of the laboratory experiment. In the former the considered mass range is larger than 1 g. In the latter the analysis was done mainly in the mass range less than 1 g. From Fig. 4, one may see the steeper mass spectrum for the larger equivalent E/M_t value, and this seems to be reasonably understood from the general consideration of the nature of high velocity impact phenomena and also the results of laboratory experiment. However, the very large exponents for three showers give rise to a question that the larger fragments were lost in these showers. Further study is needed as to this point.

4. Diogenite Shower

The Yamato meteorites in the Catalog involve 30 diogenites. These diogenites except one belong to a single shower. The shape is rounded compared with the shape of chondrites, with the average axial ratio $\langle b/a \rangle$ of 0.79. (Fig. 1b). Mass spectrum of the diogenite shower is also shown in Fig. 3, which is very flat with the exponent 0.35 ± 0.02 over the mass range of 2.5 g–700 g. It seems that the roundness in the fragment shape and the flatness of the mass spectrum are related to each other. The difference between the chondrite showers and the diogenite shower found here should be checked with the showers in the newly discovered Yamato meteorites.

5. Concluding Remarks

The following are tentatively concluded from the present analysis:

(1) The shape of chondrites is similar to the shape of basalt fragments in laboratory high velocity impact experiment.

(2) If one applies the law found by laboratory experiment to meteorite showers, the impact is "core type" destruction.

(3) Mass spectra of fragments of showers are represented by power law.

(4) Distributions of axial ratio of the fragments of each shower are similar to each other.

(5) One diogenite shower has a different character from that of the chondrite showers, the roundness in shape and the flatness in mass spectrum.

Such quantitative analysis on the destruction phenomena of meteorites has become possible for the first time by the discovery of the Yamato meteorites. Because of the preliminary character of this report, stress is laid on the the presentation of the facts, and their interpretation is avoided. Nevertheless, it would be meaningful to make some comments and speculations.

(1) Some of the fragments in a shower may not be recovered. Though the estimation of lost fragments is essentially impossible, one can guess the mass range in which the loss occurs. When a knee or a maximum in differential mass spectrum of shower is found at a small mass, it is supposed for smaller fragments to be lost. For

showers 1, 3 and 5, loss occurs below the fragmental mass of ~5 g, but for showers 2 and 4 any evidences for or against the loss were not found.

Larger fragments may fall in the separated area apart from the main part of shower, which is probable in the case of oblique falling of the original meteorite. At present, method to check the loss of larger fragment is not known, so the (M_a/M_t) values of showers are of the tentative character.

(2) Some fragments have fusion crust, which covers a part of fragment surface. The ratio of the number of fragments with crust to the total number of fragments is a significant quantity. It should be noted this ratio taken for a fixed mass range is not almost affected by the loss of some fragments. Fragments with fusion crust come from the surface part of the original meteorite, so this ratio will be large for large fragments. This seems to be true for the present five showers. For the fragment mass ranges 0–1.9 g, 2–6.9 g, 7–19.9 g and >20 g, the ratios are 29% 42%, 61%, and 80% respectively. For increasing impact energy this ratio is expected to decrease because then an original meteorite will be divided into finer pieces. Thus this ratio would be a good indicator of the impact energy. A detailed analysis will be shown later.

(3) Where is the meteorite destroyed? From the fact that some fragments have fusion crust and the others have not, the destruction occurs after the formation of the fusion crust. Incident meteorite is heated up and emits light in the upper atmosphere. The light emission ceases at about a few tens of km. Therefore, the destruction must occur either in the lower atmosphere or when the meteorite hits the ground snow or ice.

(4) Next we discuss the mechanism of destruction. In laboratories, high velocity impact experiments are done by hitting small projectile on the large rock target. By the impact a compressive shock wave grows, expanding in the rock, reflecting at its boundary. The reflected wave is a rarefaction wave, which produces a tensile stress in the rock and destroys it (FUJIWARA, 1980). The situation will be similar if the destruction of meteorite occurs when it hits the ground.

However, the situation will be different for the destruction in the atmosphere. A frictional force from air compresses the meteorite along the direction of its motion. It should be noted that the thermal stress is also acting within the falling meteorite. These two kinds of stresses will lead to destruction.

Light emission and mass loss of the meteoroid body in the atmosphere have been well studied. Further studies on meteoroids, especially on the stresses both from mechanical and thermal origins, will throw light on the present problem.

(5) Weathering may contribute to the destruction. Fresh fissures are often observed on meteorite surface (CHANG SHUYUEN, 1981). The weathering may start from these fissures and may divide further the fragments into small pieces. On the other hand, the fissures have a character of the latent breakup surfaces. If the tensile strength of the meteorite was a little lower, one would see a real breakup along the fissures. Thus the whole character of destruction may not be changed largely.

Acknowledgments

The author wishes to express his sincere thanks to Dr. A. FUJIWARA for valuable discussions, and to an anonymous referee for suggestion to add some remarks on the destruction mechanism in the last section.

References

CHANG SHUYUEN (1981): The fissures of Jilin meteorite. Mem. Natl Inst. Polar Res., Spec. Issue, **20**, 285–291.

FUJIWARA, A., KAMIMOTO, G. and TSUKAMOTO, A. (1977): Destruction of basaltic bodies by high velocity impact. Icarus, **31**, 277–288.

FUJIWARA, A., KAMIMOTO, G. and TSUKAMOTO, A. (1978): Expected shape distribution of asteroids obtained from laboratory impact experiments. Nature, **272**, 602–603.

FUJIWARA, A. (1980): On the mechanism of catastrophic destruction of minor planets by high-velocity impact. Icarus, **41**, 356–364.

LANGE, M. A. and AHRENS, T. J. (1981): Impact experiments in low-temperature ice. Lunar and Planetary Science XII. Houston, Lunar Planet. Inst., 592–594.

YANAI, K. comp. (1979): Catalog of Yamato Meteorites. 1st ed. Tokyo, Natl Inst. Polar Res., 188 p. with 10 pls.

(Received June 1, 1981; Revised manuscript received September 10, 1981)