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RAPID GROWTH OF ASTEROIDS OWING TO VERY STICKY INTERSTELLAR ORGANIC GRAINS

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ABSTRACT

We experimentally found interstellar grains covered with organic matter in an asteroid belt, and more importantly, the organic matter played an essential role in the formation of the asteroids. The sticking threshold velocityof 5 m s^{-1} of the millimeter-sized organic grains was several orders of magnitude higher than those of the coexisting silicate and ice grains. This indicated a very rapid coagulation of the very sticky organic grain aggregates and the formation of planetesimals in the asteroid region, covering even the early stage of the turbulent solar nebula. In contrast, there was no coagulation of the silicate and ice grains in the terrestrial and Jovian regions, respectively.

Subject headings: methods: laboratory — minor planets, asteroids — planetary systems: protoplanetary disks — planets and satellites: formation — solar system: formation

1. INTRODUCTION

Interstellar grains in a molecular cloud have a layered structure that is composed of a silicate core, an inner organic matter mantle, and an outer ice mantle (Greenberg 1998). The organic matter mantle can be further divided into an inner diffuse cloud organic mantle and an outer molecular cloud mantle. The interstellar grains in the cloud are heated and partially evaporate when the solar nebula is formed. The remaining core-mantle grains grow into large aggregates by collision and subsequent sticking.

Although many collision experiments have been performed using silicates (Hartman 1978; Blum & Munch 1993; Wurm & Blum 1998; Poppe, Blum, & Henning 2000) and ice (Bridges, Hatzes, & Lin 1984; Hatzes, Bridges, & Lin 1988; Higa, Arakawa, & Maeno 1998), no experiments involving organic matter have been conducted. Therefore, we performed collision experiments using an interstellar organic matter analog. Based on the experimental results, we discuss the origin of asteroids.

2. EXPERIMENTAL

Because we could not obtain interstellar organic matter, we mixed chemical reagents to form an analog of interstellar organic matter (Table 1). For molecular cloud organic matter (A), we referred to analytical data on organic matter (Greenberg & Mendoza-Gomez 1991; Briggs et al. 1992) produced by simulation experiments. Some materials have been proposed as possible analogs of diffuse cloud organic matter: hydrogenated amorphous carbon (Duley et al. 1989), quenched carbonaceous condensate (Sakata et al. 1983), UV-irradiated organic residue (Jenniskens et al. 1993; Li & Greenberg 1997), mixture of polycyclic aromatic hydrocarbons (PAHs) and uncharacterized materials (Greenberg et al. 2000), or graphitic materials (Li & Draine 2001). We used PAHs based on the analytical data of Greenberg et al. (2000) because we could not obtain large amounts of materials except for PAHs. The ratio of A to B was set at 1 : 0.63 (Greenberg & Li 1996).

Heating experiments were performed to study evaporation metamorphism and determine the distribution of interstellar organic matter in the solar nebula. The starting materials (A and B) were put into a small silica glass vessel and heated for 80 hr at a desired temperature in a vacuum chamber (10^{-6} Pa). Heating for 80 hr was found to be sufficient for applying the present experimental results to the phenomenon that occurs in the solar nebula. No change was observed after heating for 20 hr at 333 K and for few hours at other temperatures. The evolved gas was analyzed in situ with a quadrupole mass spectrometer. The residue was weighed and then analyzed by an elemental analyzer.

Head-on collision experiments were performed by the free fall of a copper sphere onto an organic matter (A) coated copper block. We used an apparatus similar to one described before (Higa et al. 1998). The thickness of the organic matter was 1 mm. The copper sphere, 1 cm in diameter, and the copper block, 12 mm in thickness, were cooled to 200–300 K in a nitrogen atmosphere. The velocities of the copper sphere were measured using a laser beam placed above the copper block and an acoustic emission sensor attached to the copper block. We used the acoustic signal and video camera image to determine whether the sphere stuck or not.

After the collisional sticking, a tensile strength between the copper sphere and the organic layer (A) was measured at 250 K by pulling of the copper sphere at a constant rate of 5×10^{-5} m s^{-1}. The pulling force in tearing the organic layer was measured using a load cell and then converted to the tensile strength.

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TABLE 1
Composition of an Interstellar Organic Matter Analog

Chemical Compounds	Chemical Formulas	Weight Percent (%)
A:		
Acetamide[a]	CH_3CONH_2	4.1
Urea	H_2NCONH_2	0.5
Ethylene glycol	$HOCH_2CH_2OH$	1.2
Glycolic acid	$HOCH_2COOH$	7.2
Lactamide[a]	$CH_3CH(OH)CONH_2$	5.4
Glycerol	$HOCH_2CH(OH)CH_2OH$	1.4
Hexamethylenetetramine	$C_6H_{12}N_4$	0.7
Indene	C_9H_8	4.7
Dimethylnaphthalene	$C_{10}H_6(CH_3)_2$	1.6
1, 4-Diisopropenylbenzene[b]	$C_6H_4[C(CH_3)CH_2]_2$	2.0
Cyclohexyl phenyl ketone[b]	$C_6H_{11}COC_6H_5$	5.0
4′-Cyclohexylacetophenone[b]	$C_6H_{11}C_6H_4COCH_3$	4.4
4-(1-adamantyl)phenol[b]	$C_{10}H_{15}C_6H_4OH$	1.3
4, 4′-Methylenebis-(2, 6-dimethylphenol)[b]	$C_{17}H_{20}O_2$	1.4
α, α'-bis(4-hydroxyphenyl)-1,4-diisopropylbenzene[b]	$C_6H_4[C(CH_3)_2C_6H_4OH]_2$	0.1
Phenanthrene[b]	$C_{14}H_{10}$	6.8
Lauric acid[b]	$CH_3(CH_2)_{10}COOH$	3.8
Sebacic acid[b]	$HOOC(CH_2)_8COOH$	3.9
Eicosanoic acid[b]	$CH_3(CH_2)_{18}COOH$	6.0
B:		
Phenanthrene	$C_{14}H_{10}$	5.2
Pyrene	$C_{16}H_{10}$	4.3
Benzopyrene	$C_{20}H_{12}$	6.7
Benzoperylene	$C_{22}H_{12}$	3.9
Coronene	$C_{24}H_{12}$	18.4

Note.—A is the molecular cloud organic matter; B is the diffuse cloud organic matter.
[a] Chemical compound for which, when we could not obtain the same chemical reagents as previous analyses, we used similar characteristic reagents.
[b] Unidentified compounds estimated from elemental compositions.

3. RESULTS AND DISCUSSION

Figure 1 shows the temperature dependence of the mass of the evaporation residue. Most of the oxygen- and nitrogen-containing materials (A) were evaporated below 373 K, and the polycyclic aromatic hydrocarbons (B) vanished below 453 K. According to an in situ mass spectral analysis, we found that most of the A material decomposed thermally into simple molecules, such as CH_4, NH_3, H_2O, CO, and CO_2. Note that the evaporation temperature of diffuse cloud organic matter depends on the composition of starting materials used. Although PAHs are not fully representative of the bulk carbonaceous grains in diffuse interstellar medium, the fact that the diffuse cloud organic residues are more refractory than PAHs does not disprove but rather strengthens the conclusion on the stickiness of molecular cloud organic matter (A), which we discuss later.

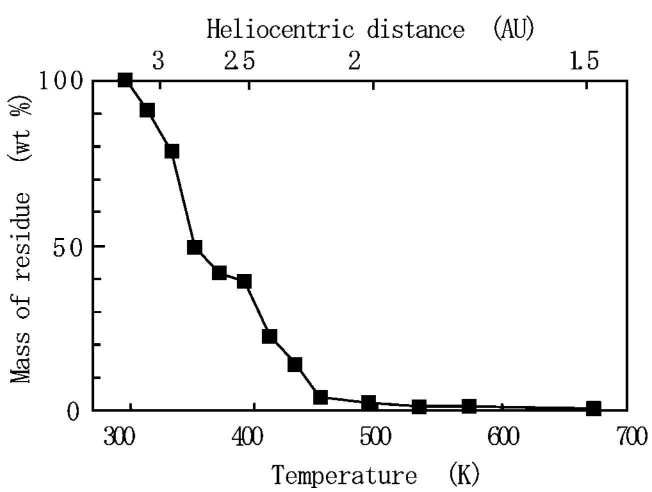

Fig. 1.—Temperature dependence of the mass of evaporation residue. Upper abscissa shows the corresponding heliocentric distance in the final stage of the accretion disk, which was calculated using the Bell et al. (1997) model for the accretion rate of 10^{-7} yr^{-1} and the viscous efficiency $\alpha = 0.004$.

The temperature distribution of the final stage of the accretion disk in heliocentric distance (Bell et al. 1997) is shown in the upper abscissa of Figure 1. From this figure we determined the distribution of organic matter in the accretion disk stage of the solar nebula. The distribution composed diffuse cloud organic matter of greater than 2.2 AU and molecular cloud organic matter of greater than 2.6 AU. Most of the interstellar organic matter was evaporated at 2.2 AU. Note that the heliocentric distances determined in this way depend greatly on the accretion model itself and pm the parameters used.

Figure 2 presents the experimental results while showing the condition for sticking and repulsion in a velocity versus temperature diagram. In the diagram, the sticking threshold velocity increases with increasing temperature, attaining a maximum value of 5 m s^{-1} at around 250 K, and then it decreases. The tensile strength between the copper sphere and organic layer after the collisional sticking at 250 K is 10^5 Nm^{-2}. In collision experiments with millimeter-sized silicates and ice, no sticking was observed, even at very low collision velocities, namely, 0.15 m s^{-1} for the silicates (Hartman 1978; Blum & Munch 1993) and 1.5×10^{-4} m s^{-1} for the ice (Bridges et al. 1984; Hatzes et al. 1988; Higa et al. 1998). It should be noted that sticking was observed, but only for micrometer-sized silicates (Wurm & Blum 1998; Poppe et al. 2000). For millimeter-sized particles of ice, graphite, and quartz, Chokshi, Tielens, & Hollenbach (1993) theoretically estimated the critical velocities for sticking to be on the orders of between 10^{-4} and 10^{-2} m s^{-1}. As a result, we conclude that the sticking threshold velocity of millimeter-sized organic matter is several orders of mag-

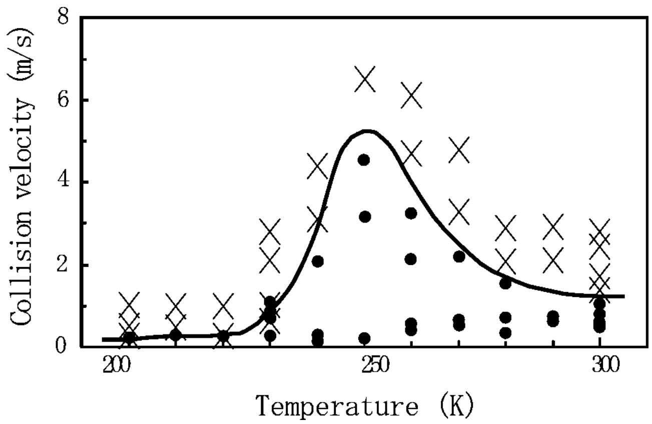

FIG. 2.—Conditions for sticking during the collision of a copper sphere onto an analog of molecular cloud organic matter (A) layer on a copper block. Filled circles and crosses represent sticking and repulsion, respectively. Solid line shows the sticking threshold velocity of an interstellar organic matter analog.

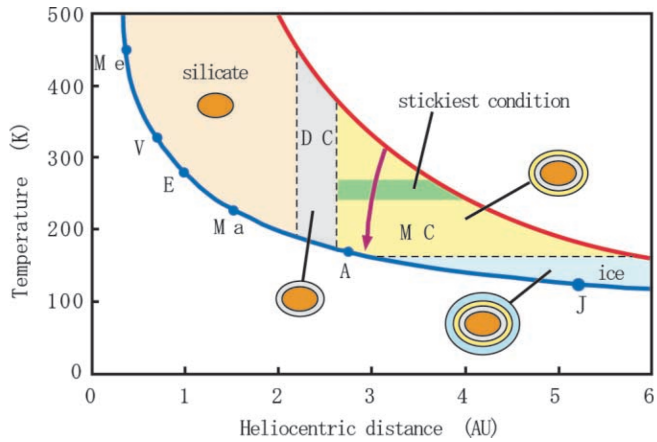

FIG. 3.—Occurrence of grain surface materials, silicate, molecular cloud (MC) and diffuse cloud (DC) organic matter and ice in the protosolar nebula. Structure of grains in the respective regions are also shown. Red line shows the temperature distribution of the accretion disk, identical to that in Fig. 1, and blue line with filled circles (planets) shows the passive disk (Hayashi et al. 1985). The stickiest condition of the millimeter-sized organic grains is shown by the green solid line. Arrow shows the cooling history of the grains/grain aggregates.

nitude higher than the velocities of silicate and ice. This clearly shows that millimeter-sized organic grain aggregates stick together to form larger aggregates even at the turbulent stage of the solar nebula, as proposed by Weidenschilling & Cuzzi (1993).

Here we discuss why organic materials are very sticky compared with silicates and ice. At temperatures higher than 220 K, the organic materials (A) are not a perfect solid but a viscoelastic material. Then, it may be possible for it to behave as a liquid bridge and attract the copper sphere. The sticking force between particles due to the liquid bridge (Erle, Dyson, & Morrow 1971) is one order of magnitude larger than that due to van der Waals force (Chokshi et al. 1993). But it is not strong enough to explain the observed stickiness of organic matter (A). The viscoelastic behavior during collision—kinetic energy dissipation by the deformation/flow of organic matter during collision—should be considered to decrease the rebound velocity of the sphere. After the reduction of the rebound velocity, the sphere could be easily stuck by the forces discussed above. This could be the mechanism to cause the strong stickiness of the organic materials (A).

Figure 3 shows the various kind of materials that cover the surfaces of grains during the period of evolution from an accretion disk to a passive disk. Because most of the interstellar organic matter is evaporated at 2.2 AU (Fig. 1), only silicate minerals smaller than 2.2 AU remain. The cause of the vertical boundary between the silicates and organic matter is as follows. Because organic matter is decomposed thermally through evaporation, it does not recondense when the solar nebula is cooled to the temperature range of the passive disk (Hayashi, Nakazawa, & Nakagawa 1985). On the other hand, ice crystals recondense at temperatures lower than about 160 K (>3 AU). This figure also shows the stickiest condition determined from the collision experiments (Fig. 2). In 2.6–3.8 AU, grains pass through the region with decreasing nebula temperature, and grains effectively coagulate. Therefore, we conclude that the coagulation of grain aggregates and the formation of planetesimals occur more rapidly in the asteroid belt than in terrestrial and Jovian regions.

4. ORIGIN OF ASTEROIDS

In this section we discuss the application of the experimental results to the origin of asteroids. The important features of asteroids are summarized as follows: (1) the quantity of solid material in a present-day asteroid belt is 3–4 orders of magnitude smaller than that assumed by the standard solar nebula model (Hayashi et al. 1985) and (2) there are many small bodies compared to usual-sized planets.

Feature 1 is usually explained as follows (Wetherill 1989): there originally was the expected amount of materials there, but these materials were removed after the formation of large asteroids by nongravitational forces or external gravitational perturbations. There are two ways to explain feature 2: (*a*) larger bodies were broken by collisional fragmentation (Wetherill 1989) or (*b*) small bodies could not grow owing to the brittleness of iron (Matsui & Mizutani 1977).

We discuss feature 1 first. Our idea differs from the above model in terms of the timing of removal. As has already been shown, the coagulation of grain aggregates occurs very rapidly in an asteroid belt owing to the sticking effect of organic matter in spite of the turbulent conditions. The formation of planetesimals results from such coagulation of grain aggregates, as shown by Weidenschilling & Cuzzi (1993). As the planetesimals are formed, aggregates of 1 m in size rapidly fall inside owing to the strong gas drag (Adachi, Hayashi, & Nakazawa 1976); as a result, the materials of the asteroids decrease in 2.6–3.8 AU very rapidly. It has been suggested that the depletion of materials is due not to removal subsequent to the formation of large asteroids (Wetherill 1989) but to removal by inward-falling aggregates under the gas drag, which occurs simultaneously with planetesimal formation (Weidenschilling & Cuzzi 1993).

The reason why there are many small bodies compared to usual-sized planets (feature 2) is not the collisional fragmentation as hitherto considered in explanation *a* (Wetherill 1989) but the depletion of materials as discussed above. The depletion causes the growth of asteroids to stop. Accordingly, the mechanism of our model is different from explanation *b*. We conclude that interstellar organic matter played an essential role in the formation of asteroids.

All previous discussions on the evolution of planets have been based on the assumption that planetesimals are formed almost simultaneously, more precisely speaking, from inward to outward. However, our model suggests that the formation of planetesimals in the asteroid belt occurs first not owing to gravitational instability, but instead owing to the coagulation of grain aggregates, and that the asteroids' parent planetesimals are the oldest bodies in the solar system. Furthermore, the inward falling of materials by gas drag is important for the supply of materials to the Earth and Venus regions.

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