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Energy Loss and Sticking Mechanisms in Particle Aggregation in Planetesimal Formation

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A crucial step in the development of planetary systems is the aggregation of small solid particles to form planetesimals in gaseous protoplanetary disks such as the primordial solar nebula. Among small (centimeter-sized) aggregates for which self-gravity is negligible, a sticking mechanism is needed to hold the aggregate together, even when the relative velocities are very low. A similar cohesive process may also determine the size distribution of particles in planetary rings. In order to provide the crucial data, we carry out experiments to investigate the contact sticking that occurs for surfaces coated with different types of frosts, deposited at various (low) temperatures and pressures relevant to solar nebula conditions. Our preliminary measurements show that several types of frost-coated surfaces stick together when brought into contact at very low temperatures (~100 K), but the sticking forces depend on the deposition conditions. For ice particles covered with H_2O and CO_2 frost: (1) the energy loss in collisions depends strongly on the impact speed and surface structure, and (2) particle "sticking" can occur if the impact speed is sufficiently low. Static sticking experiments using methanol (CH_3OH) frost demonstrate that methanol is also an effective "sticky" frost. We apply these results to planetesimal formation and suggest that a layer of surface frost provides both the energy loss and the contact sticking required for the formation of large aggregates. © 1996 Academic Press, Inc.

1. INTRODUCTION

An accepted model for the formation of the Solar System is that the planets were formed from a primordial solar nebula surrounding the protosun (Cameron 1978, 1995). Recent detection of protostellar disks indicates that the necessary environment for planetary-system formation is commonly found around young stellar objects (Sargent and Beckwith 1987, 1991). According to current theories, the formation of terrestrial planets progresses through at least four stages: (1) the condensation of heavy elements into volatile and refractory grains (Völk *et al.* 1980, Nakagawa *et al.* 1986); (2) the formation of planetesimals through cohesive collisions of the grains (Kerridge and Vedder 1972, Hartmann 1978, Weidenschilling 1984, 1987, Weidenschilling and Cuzzi 1993) or through gravitational instability at larger sizes (Safronov 1969, Goldreich and Ward 1973); (3) the coagulation of planetesimals into protoplanets (Safronov 1969, Hayashi *et al.* 1977, Greenberg *et al.* 1978, Wetherill 1980, 1989, 1990, Hornung *et al.* 1985, Lissauer and Stewart 1993, Aarseth *et al.* 1993); and (4) the clearing of residual planetesimals (Duncan and Quinn 1993). The formation of protogiant planets may proceed through the initial emergence of solid cores, analogous to the prototerrestrial planets, through a similar sequence of events, followed by the accretion of gas from the solar nebula (Podolak *et al.* 1993). Because of the evolution of the primordial solar nebula, these four evolutionary stages may occur concurrently rather than sequentially. As matter in the solar nebula is depleted due to viscous evolution, the gaseous temperature decreases (Lin and Papaloizou 1985, Ruden and Lin 1986) such that condensation and the growth of grains occur over an extended period of time, in which the condensates from earlier epochs may have formed grains or grown substantially to form planetesimals and protoplanets. Nevertheless, the four stages

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may be clearly distinguished by the dominant physical processes which regulate their growth. For example, grain condensation in the first stage is determined by molecular interactions, whereas the clearing of planetesimals during the final stage is governed by long-term orbital instabilities. The second and third stages are separated naturally by the formation of large planetesimals which are primarily bound by self-gravity rather than material strength.

The need for some type of surface-sticking force arises from the very small self-gravity of small planetesimals (~1 m in diameter) and the correspondingly very small escape velocity ($\lesssim 1$ mm $\sec^{-1}$). Consequently, only aggregates that are essentially not rotating (surface rotation speed $\lesssim 1$ mm $\sec^{-1}$) and are not subject to impact forces greater than a few dynes would remain intact. It is unlikely that such conditions would persist over significant time scales in the early solar nebula. If surface sticking occurs, planetesimals can grow through this crucial stage of development. Throughout this paper we will use the terms *sticking* and *adhesion* to refer to any mechanism that holds two objects together. The *sticking force* is defined as the force necessary to separate the two objects.

In this paper, we report on experiments which examine the growth process of solid particles during the second stage of this sequence. These particles provide the initial building blocks for larger planetesimals. They may also lead to the formation of meteorites and asteroids. Early investigations in this area were carried out through collision experiments (Kerridge and Vedder 1972, Hartmann 1978, 1985) at relatively high speeds (m $\sec^{-1}$ to km $\sec^{-1}$). In these studies, no sticking was observed, but high energy loss and a correspondingly large decrease in relative speeds occurred when particle surfaces were coated with a regolith of rock powders. Theoretical investigations have concentrated on numerical simulations of particle collisions. The majority of such simulations use a simple "sticking probability" and do not address the complicated issue of the actual mechanism by which sticking occurs. The most widely cited theoretical work is based on a one-dimensional idealized turbulent model for the solar nebula gas (Weidenschilling 1980, 1984, Weidenschilling and Cuzzi 1993). The outcome of the simulation appears to depend only weakly on the assumptions for the gas in the solar nebula (Battaglia 1987). However, the rate of growth of solid particles strongly depends on two major unsolved problems, "the degree to which particles stick together in collisions, and the mechanisms by which they adhere" (Weidenschilling and Cuzzi 1993). The latter issue in fact determines whether particles may remain bound in subsequent collisions because of the large impact forces. These forces depend on the velocity dispersion of the particles, which in turn depends on their size (Völk *et al.* 1980, Mizuno *et al.* 1988, Markiewicz *et al.* 1991). Very small (<1 cm) particles essentially comove with the turbulent flow. The motion of very large (>10^4 cm) particles is essentially unaffected by turbulent motion, but large particles do settle toward the disk's midplane due to the drag induced by the main flow. The collisions between partially coupled intermediate-sized particles may result in large impact velocities which could disrupt small aggregates if they are bound only by their own self-gravity. In fact, numerical simulations (Weidenschilling 1984, Battaglia 1987, Weidenschilling and Cuzzi 1993) show that the impact from these collisions often leads to a particle's disruption unless its internal density is low as a consequence of the particle's fractal structure (Meakin and Donn 1988, Weidenschilling 1989). The problem, then, is how do small particles aggregate to form planetesimals which eventually decouple from the turbulent flow and thus must undergo some high-speed collisions?

In principle, these uncertainties might be simply resolved by experimental data on the condition for cohesive collisions and the sticking strength of coagulated particles. For very small particles (<1 mm), electrostatic forces (fluctuating dipole or Van der Waal forces) clearly are important. However, the extrapolation of such a binding mechanism to large particles is questionable. In principle, energy dissipation of colliding particles reduces their dispersive motion. Through a series of laboratory experiments using ice particles (Bridges *et al.* 1984, Hatzes *et al.* 1988, Supulver *et al.* 1995), we found that although collisional energy loss can dramatically reduce the average collision speeds when they are large, collisions become elastic in the low-velocity limit. The quantitative measure of the energy lost in collisions is provided by the coefficient of restitution, ε, defined by $\varepsilon = v_{\text{out}}/v_{\text{in}}$, where v_{in} is the relative velocity of the particles before collision, and v_{out} is the relative velocity after collision. Our studies of water ice particles show that for 500-g particles, the coefficient of restitution approaches unity at low collision speeds (Hatzes *et al.* 1988), so it is difficult to reduce the relative speed below 1 mm $\sec^{-1}$ for water-frost-coated particles; for surfaces coated with harder materials the relative speeds in equilibrium could be even higher. Using these results, Salo (1992) and Richardson (1994) show that particles can cluster and form wakes in planetary ring systems. However, these clusters are easily disrupted (for example, by impact forces from slightly faster particles) and will break up in a few orbital periods if a significant surface-sticking mechanism is not operative.

There have been several previous attempts to obtain experimental information on the probability of cohesive collisions. Hartmann (1978) found that the presence of a surface layer of granular particles (a regolith composed of rock and mortar powders) on a clean rock surface reduced ε for irregular rock projectiles from 0.5 to 0.06 (at fairly high impact speeds of several m $\sec^{-1}$) as the depth of the surface layer approached the diameter of the impacting particle. When ε is very low, the rebound velocity could drop below the escape velocity of the target, and the likelihood of the impacting object remaining in contact with the target increases; no actual cohesive sticking occurred in these experiments. However, if the impactor–target assemblage is rotating significantly (surface speed $\gtrsim 1$ mm sec^{-1}), then the two particles may, depending on their sizes, separate if no surface sticking is present. Weidenschilling (1988) found that collisions between unconsolidated pumice and dust could lead to mass loss when the impact speed exceeds $\sim 10^3$ cm sec^{-1}.

Pinter *et al.* (1989) and Blum (1990) observed coagulation among sub-centimeter-sized glass spheres coated with a thin layer of hydrocarbons when they collide at speeds up to $\sim 10^2$ cm sec^{-1}. Since the conditions under which these two experiments were carried out are far removed from those expected in the solar nebula, it is not clear whether they are directly relevant in the context of mechanisms for planetesimal formation. For example, the cohesive ‘‘glue’’ that binds small particles in the centimeter to meter range may well depend on the ambient conditions and must depend on the types of (surface) materials present, particularly the ‘‘frosts’’ of the volatile components which have condensed on particles and grains. The temperature and density of the nebula gas not only are functions of radial distance from the protosun and height above the midplane, but also are determined by the evolution of the nebula (Ruden and Lin 1986). Since the condensation of grains occurs under specific conditions (Lewis 1972), different types of planetesimals may be formed at various locations in the solar nebula (Cameron and Fegley 1982). Further complications may occur for some range of radii where the midplane temperature is higher and the surface temperature is lower than the condensation temperature of the grains or some volatile component deposited on their surface. As the grains comove with the gas through these regions, their surfaces may be altered repeatedly by intermittent condensation and sublimation. The cohesive probability and sticking strength would almost certainly be determined by these environmental conditions.

In thousands of collisions of water ice particles (at very low speeds, from 10^{-2} to 1 cm sec^{-1}) that we have carried out over the past several years for temperatures in the range 90 to 150 K and ambient pressures of 10^{-5} to 760 Torr, we have never observed any sticking between smooth or rough surfaces *unless* we have coated the surface with a layer of frost. Whether or not sticking occurs in very-low-speed collisions of ice particles depends critically on the surface structure of the frost deposited at low temperatures. Similarly, no evidence for sticking was found in the collision experiments of Blum and Münch (1993) in $\sim$500 collisions (using small fluffy dust balls roughly 1 mm in size) at speeds from 14 cm sec^{-1} to $\sim$1 m sec^{-1}. Instead, fragmentation occurs in the high-velocity limit. The upper limit for a possible sticking force in our collision experiments without frost is $\sim$1 dyn (for a contact area of $\sim$1 mm^2), which is negligible compared to the impact forces. Thus, these experimental results are in strong disagreement with the estimated sticking forces calculated using the model of Chokshi *et al.* (1993).

The only condition under which we have observed significant sticking for large particles ($\sim$5 cm in diameter) is when a thin layer of porous frost has condensed on the contact surface and the impact speeds are low (Hatzes *et al.* 1991). However, the presence of frost alone does not guarantee sticking in low-speed collisions. Compacted frost shows no measurable sticking (Hatzes *et al.* 1988, 1991) at very low impact speeds (0.01 cm sec^{-1}), and measurements of the static sticking force between surfaces coated with water frost indicate that the surface structure is crucial (Bridges *et al.* 1996). For example, in a series of measurements using dense, thick (up to 1 mm thick) water frost, *no* static sticking force was observed even for freshly deposited frost (at temperatures near 100 K). However, thin water-frost layers have resulted in quite large sticking forces (up to 10^4 dyn) for similar temperatures. Hatzes *et al.* (1991) postulated that this sticking is due to the mechanical interpenetration and interlocking of ‘‘fingers’’ of frost, similar to the ‘‘sticking mechanism’’ by which the commercial material Velcro adheres. The other set of collision experiments which has shown coagulation (Pinter *et al.* 1989, Blum 1990) used paraffin-coated aggregates. In this case the paraffin provides the surface sticking force. Although the paraffin-coated particles are not directly relevant to planetesimal formation, these experiments, together with our sticking experiments using porous frost-coated surfaces, clearly indicate that sticking can sometimes be achieved if the surfaces can deform. If a deformable layer is not present, as, for example, in a collection of hard silicate particles, it is unlikely that aggregation will ever occur. These results lead us to the conclusion that the long-term cohesive aggregation of small planetesimals is not easy to achieve. Since surface sticking in the solar nebula may well have depended on the evolution of the gaseous components of the nebula and the local conditions within the nebula at a particular time (i.e., composition of particles from earlier epochs, surface temperature of the planetesimals that have formed), the stable growth of large particles from smaller ones is probably not a continuous process. Consequently, the assumption of a constant average sticking probability is a major simplification which is at best questionable and much more likely wrong. Models for cohesive particle sticking clearly need to be developed for different possible conditions in the primordial nebula and included in calculations of planetesimal formation.

In this paper, we present a series of experiments in order to delineate the necessary conditions for cohesive collisions. We focus here on the relatively cool regions of the nebula with low particle surface temperatures and consider the dynamics of low-speed particle collisions: the energy loss; the impact forces; and, in particular cases, the sticking forces that are present. We first review briefly, in Section 2, our work on the dynamical properties of ice particles, with and without a surface layer of H_2O frost, and then discuss our recent work on H_2O, CO_2, and CH_3OH frost. The dynamic measurements were performed in an environment which closely simulated the conditions in planetary rings (Bridges *et al.* 1984) and have provided insight into the ring dynamics (Hatzes *et al.* 1988, 1991). However, they are also relevant to a wider range of protoplanetary dynamics. In particular, we consider the role these results play in the formation of planetesimals in Section 3. Water, CO_2, and methanol have all been observed in comets (Mumma *et al.* 1993), which are considered to be largely unaltered remnants from the era of planetesimal formation. These molecules were present in the outer solar nebula when planetesimals were forming and must have played a role in forming frosts which, we propose, provided the "glue" which held small aggregates together.

2. RESULTS OF STUDIES OF ICE PARTICLE COLLISIONS

In this section we briefly review the results we have obtained from extensive studies of collisions of water ice particles to provide a background for the discussion in Section 3. We also report new results on water-frosted and CO_2-frosted water ice particles as well as methanol-frosted surfaces as a first step toward a more general understanding of the role of surface frosts. In our previous work, we have studied ice particle collisions at low speeds to gain insight into the dynamics of Saturn's rings. The main questions we have investigated are: (1) the energy loss that occurs in low-velocity collisions of water ice particles (a small particle, ~5 cm in diameter, colliding with a flat ice surface), with and without a surface layer of frost present; (2) the duration of the collision (which determines impact forces); (3) the extent to which erosion occurs in these low-speed impacts; and (4) the sticking forces, F_s, in the few cases for which sticking has been observed. Details about the experimental apparatus and procedures are given in Supulver *et al.* (1995). An additional feature of the apparatus not discussed in that paper is the ability to "catch" the ice particle after a collision using computer feedback control of the particle position. This feature is important in studies of the sticking force at low speeds.

2.1. Previous Work

First consider the case of smooth frost-free surfaces. In Fig. 1a (from Hatzes *et al.* 1988), we plot the coefficient of restitution, ε, as a function of the normal incident velocity v_n. Note that ε is very high and approaches unity at very low impact speeds (below 0.05 cm sec^{-1}). No sticking is observed in any measurement of collisions with smooth clean surfaces, and the collisions are always extremely elastic. Clearly, such particles would not aggregate.

The results in Fig. 1a pertain to normal (radial) impacts of an ice particle with a flat ice surface. Glancing collisions, however, certainly occurred in the planetesimal disk (as well as in planetary rings), and the collisional properties of the individual planetesimals (or ring particles) under such conditions were important in determining the dynamics of the disk as a whole (see Shu *et al.* 1985, Araki 1988, Aarseth *et al.* 1993). Supulver *et al.* (1995) investigated glancing collisions of frost-free ice surfaces. No sticking was observed in any of these collisions, although ε was, as a rule, lower for glancing collisions than for radial collisions.

In Fig. 1b (from Hatzes *et al.* 1988) we plot ε vs v_n for water-frost-coated particles. Most of the data in this figure are for compacted frost and were collected after many collisions had occurred at the same point on the surface. For compacted frost surfaces (and also surfaces roughened by differential sublimation), the fractional energy loss $(1 - \varepsilon^2)$ can be small at very low speeds, $v_n < 0.05$ cm sec^{-1}, but is often greater than 75% at speeds of only 2 cm sec^{-1}. An even larger energy loss is observed for an uncompacted porous frost-like surface layer. The energy loss per collision is initially very high ($\varepsilon \approx 0.3$) but decreases as the frost is compacted, and ε increases to the values shown in Fig. 1b (see inset figure in Fig. 1b; from McDonald *et al.* 1989). For low speeds the compaction of the surface frost occurs slowly, typically requiring 5–10 collisions. Similar results have been obtained for different temperatures (100–200 K), different ambient pressures, and different radii of curvature (Hatzes *et al.* 1988). Clearly, a layer of compacted water frost provided an effective mechanism for removing kinetic energy in particle collisions at moderate speeds, but this mechanism becomes much less effective at speeds below 0.5 cm sec^{-1}.

Hartmann (1978) observed a similar decrease in ε for high-speed (1–10 m sec^{-1}) collisions between particles coated with a regolith of rock and mortar powders. This mechanism certainly could operate in the solar nebula to reduce planetesimal relative velocities in high-speed collisions; however, the collisions may grow more elastic as the relative speed decreases. We have observed this effect for particles coated with water frost, as discussed above. At low impact speeds, the regolith would be more rigid, and the collisions would become more elastic. Therefore, such particles could not aggregate merely through a complete damping of relative kinetic energy; a surface-sticking mechanism would ultimately be required to bind the objects together.

The erosion of particle surfaces is particularly important when considering particle growth. Conditions must be such that the collisional impacts do not erode the surfaces faster

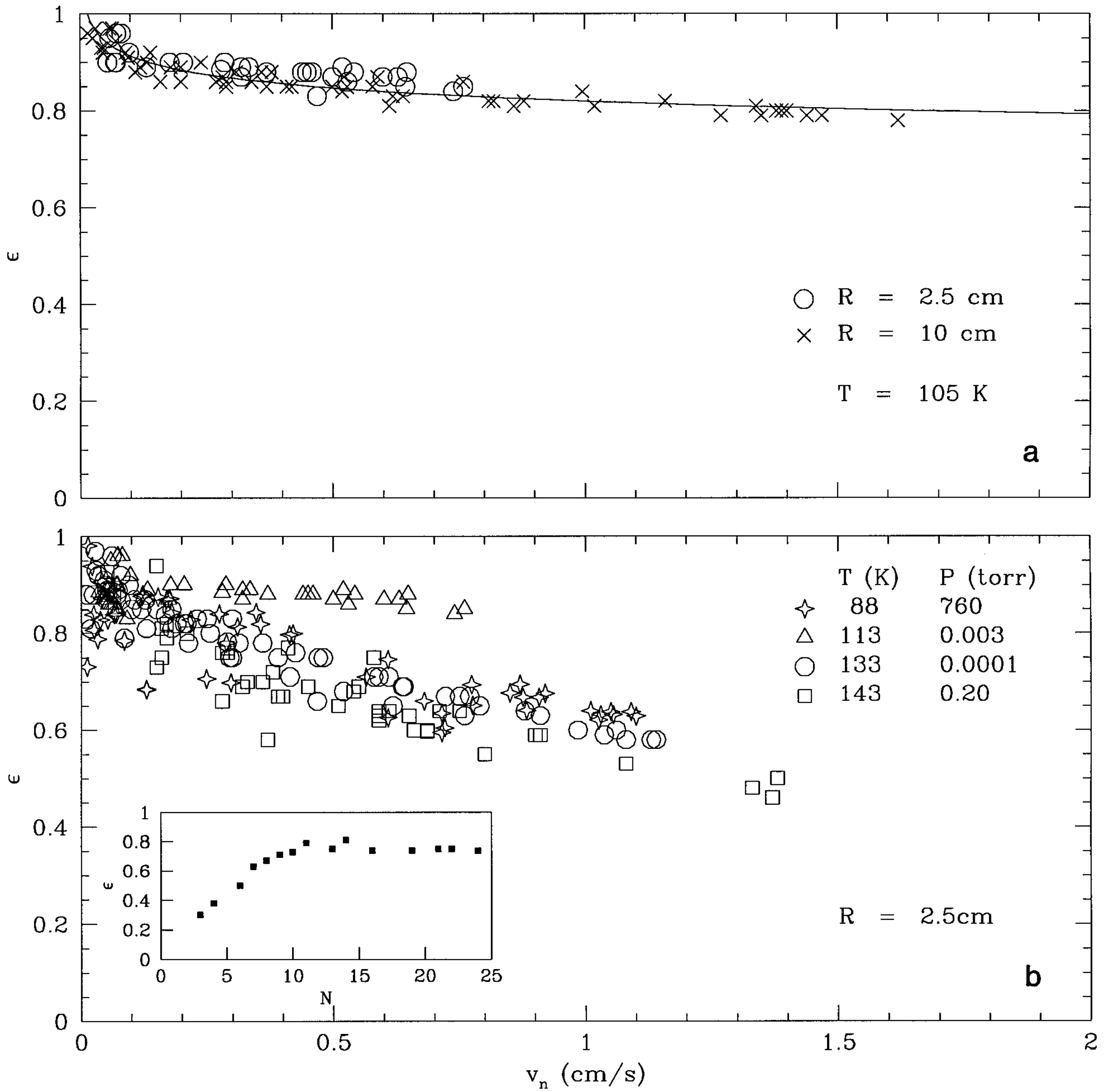

FIG. 1. (a) Coefficient of restitution as a function of radial impact velocity for two very smooth water ice spheres with two different radii of curvature (2.5 and 10 cm). The flat ice surface in this case is also very smooth. The line drawn represents a power law fit to the data. (b) Coefficient of restitution as a function of radial impact velocity for several experimental runs using a single radius of curvature (2.5 cm) for ice spheres and flat ice surfaces, both coated with a layer of H_2O frost. The temperature and pressure at which the data were taken are indicated in the figure. The inset figure shows the coefficient of restitution ε as a function of collision number, N, at constant impact velocity (0.5 cm sec^{-1}) for an ice sphere and flat ice surface, both coated with a layer of fresh H_2O frost. The value of ε is very low for the first few collisions when the frost is fresh and uncompacted, but increases steadily and then levels off at an equilibrium value when the frost becomes compacted.

than they are built up by the growth mechanisms. For the water ice particles considered above, we have investigated the erosion and transfer of mass between particles using a dye in one of the particles (McDonald *et al.* 1989). For speeds below 2 cm sec^{-1}, the mass transfer rate between water ice particles (including particles with compacted frost surfaces) is small ($<10^{-5}$ g per collision) and would likely not be an important constraint on aggregation if energy loss mechanisms are sufficient to reduce the relative velocities below 2 cm sec^{-1}. At slightly higher speeds (4–10 cm sec^{-1}) the surface of the ice particle clearly fractures, and we expect increased erosion to occur although we have not measured the rate. Consequently, for icy surfaces, erosion would likely be a serious constraint to particle growth until the relative velocities fall below some critical speed which we estimate to be in the range of $\sim$10 cm sec^{-1}.

At low speeds, we find that (water) frosted ice particles will stick together when the frost is fluffy and has not been compacted (Hatzes *et al.* 1991). The sticking force, F_s (i.e., the force required to separate the particles), depends on the impact speed preceding sticking. For very low speeds, the sticking force first increases with increasing impact speed. We attribute this to an increasing interpenetration of the frost layer on each surface. At significantly higher speeds (~1–2 cm sec^{-1}), the frost becomes compacted, and no measurable sticking occurs in subsequent collisions.

2.2. New Results

The duration of an impact, t_i, which provides a measure of the average impact force, can be estimated by a detailed analysis of the collision. In Fig. 2a, we plot the vertical position of the particle, x, as a function of time, t. The data in Figs. 2a and 2b were taken with the two-dimensional pendulum (Supulver *et al.* 1995) operating in one-dimensional (radial) mode. The collision time for this interaction is the time between the two arrows (the region for which $x(t)$ is nonlinear). For fast collisions on clean surfaces, the contact time is very short—too short for our apparatus to measure easily (time constant ~1 msec)—and the estimated impact forces are large, often larger than 1 N. However, for low-speed collisions with frost-coated surfaces (100–300 μm thick), the contact time can easily be of order 600 msec, as shown in Fig. 2a. (This impact time is much larger than typical contact times found by Hatzes *et al.* (1991), who observed an impact time of $\lesssim$0.1 sec, due to the differing characteristics of the frost layers used in the two experiments.) If the contact surfaces are coated with frost, the impact forces will be greatly reduced, but will still not be negligible. For example, consider a 1000-g object moving at the low relative speed of $v = 0.15$ cm sec^{-1} with $t_i = 0.6$ sec. Then for typical collisions, the impact force can be estimated from $F_I = P/t_i$, where P is the momentum. For the above example, $F_I = 250$ dyn, a large force when compared to the gravitational force exerted on a 10-cm particle on the surface of a 1-km object (several dynes for particle densities near 1 g cm^{-3}). This impact would disrupt a 1-km object composed of many smaller particles held together only by gravitational forces. However, such an impact might not disrupt an aggregate held together by the cohesive force of frosts (see Fig. 3 and discussion below).

We find that the frost bond is elastic and can be stretched like a spring until it breaks. In Fig. 2b, we plot the position of a particle, initially stuck to a flat surface after a low-speed ($\approx$0.25 cm sec^{-1}) radial collision, as a function of the force applied normal to the surface in the direction which would separate the particles. At the breaking point (we define the force at the breaking point to be the sticking force F_s), the particle suddenly accelerates rapidly away from the flat surface. The forces observed in these measurements were nearly an order of magnitude larger than those reported by Hatzes *et al.* (1991). This large difference is important in possible applications to aggregates.

Results from such sticking experiments are shown in Fig. 3. Typical values of F_s are several hundred dynes for the moderate frost layer thicknesses used (~300 μm), but in a few cases, values of F_s greater than 1000 dyn have been observed. In general, the data were taken in order of increasing impact velocity so that initial high-velocity impacts did not damage the frost. The impacts were purely radial; again, in these experiments we use the two-dimensional pendulum in the one-dimensional mode. The three different symbols represent three different frosting runs. In each run, a frost layer was deposited on the two ice surfaces at an ambient pressure of 150 Torr and temperatures between 100 and 110 K. The iceball was then made to impact the flat surface at several different (radial) impact velocities, and the frost sticking force was measured after each impact (at an ambient pressure of 1 atm). Data were taken over temperatures ranging from 110 to 150 K; for each run, however, data at the impact velocities corresponding to the largest frost sticking forces were recorded in the narrow temperature range of ~120–130 K. The differences in F_s in the different runs, then, can be attributed to the frost layers themselves and not to external environmental factors such as temperature or ambient pressure.

In the initial run (Run 1), frost was deposited directly on clean ice surfaces. The sticking forces for this frost are quite high. The frost used for Run 2 was deposited on the same ice surfaces 24 hr later, after most of the previous frost layer had sublimated away (the apparatus warmed to ~245 K and was then cooled again to ~95 K during that period of time). The sticking forces are somewhat lower than in Run 1. Nearly 24 hr later (after another warming and cooling cycle of the apparatus), the frost for Run 3 was applied. The sticking forces for this run are the lowest observed. The warming and cooling cycles likely allowed most of the frost to sublimate away, so that each frost layer was applied to nearly frost-free ice surfaces. However, it appears that either enough frosty material remained on the ice after each cycle or the sublimation process created a surface roughness (Hatzes *et al.* 1991) on the iceball which changed the morphology of the deposited frost in subsequent runs. Applying frost to an already rough surface decreases the sticking force below what one would expect for frost deposited on clean surfaces. The applied frost, which condenses on the ice surfaces both via small snowflake particles formed in the ambient gas and directly from the vapor phase, may fill in gaps in a rough surface instead of forming the fluffy dendritic structures which provide strong frost bonds.

The data in Fig. 3 show that the sticking force increases roughly linearly with impact velocity up to ~0.3 cm sec^{-1}, at which point the frost layers are damaged and do not stick effectively. We analyze this linear dependence at low speeds by considering the impact force F_I of the iceball

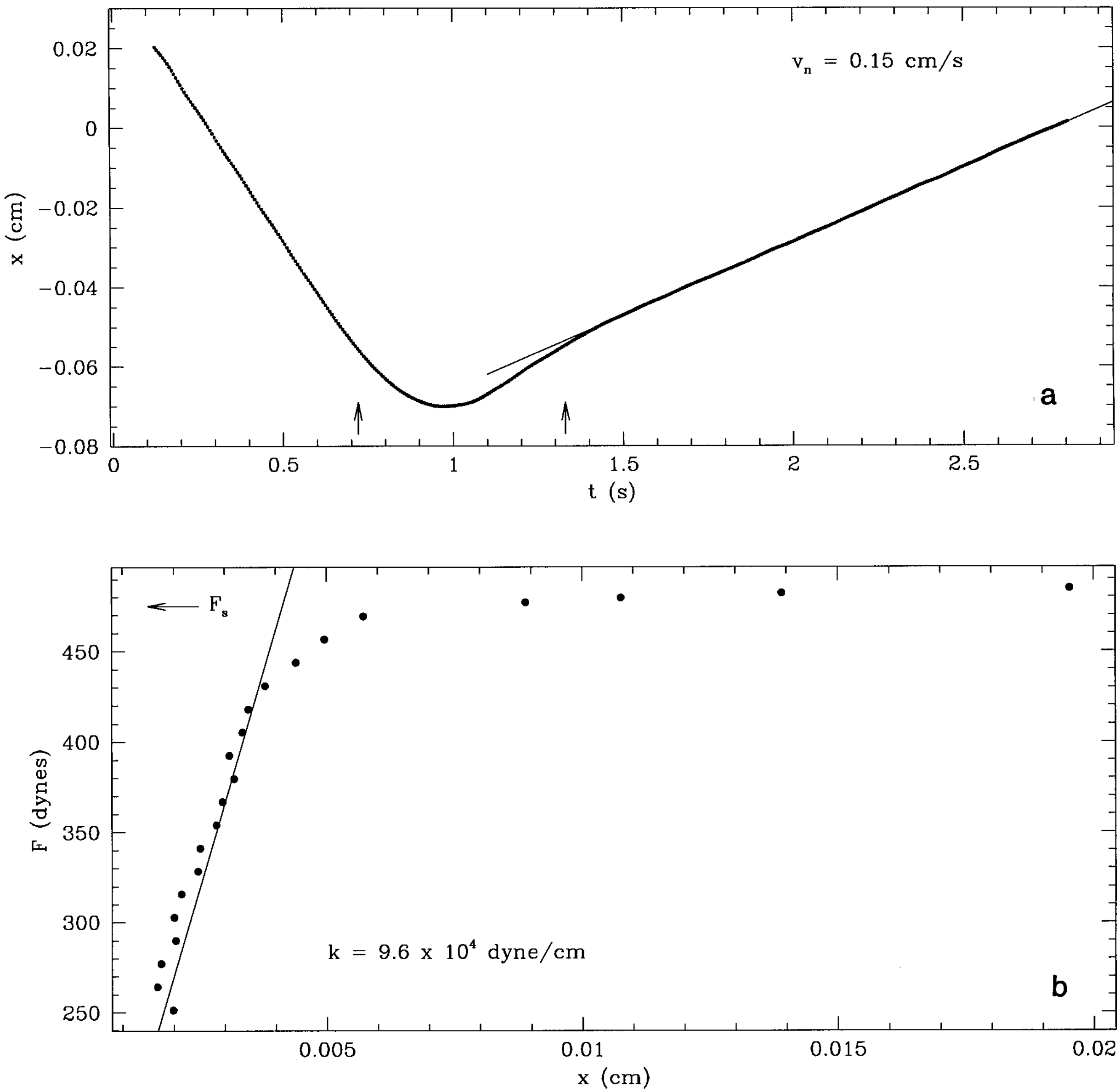

FIG. 2. (a) Close-up of a low-speed (0.15 cm sec^{-1}) nonsticking collision between an ice sphere and a flat ice surface, both coated with slightly compacted H_2O frost. After impact, the motion of the ice sphere deviates from a constant velocity motion for the first 200 μm of the outbound trajectory due to the cohesive force between the two frost layers. Note that the duration of the collision is of order 600 msec (the time between the two arrows). (b) The displacement of a "stuck" ice sphere as a function of an applied external force after a sticking collision. The slope of this $F(x)$ relationship yields a measure of the spring constant k. Above a force of ~475 dyn, the displacement increases rapidly, signifying that the cohesive bonds have been broken. This yields a measure of the sticking force, F_s.

colliding with the brick, $F_I = (m_{\rm eff} v_n)/t_i$, where $m_{\rm eff}$ is the effective mass of the iceball ($\approx$500 g), v_n is the impact velocity, and t_i is the impact time. We model the frost as a spring (Hatzes *et al.* 1991), with stretch x proportional to the applied force F: $|F| = Kx$. Then the particle–spring system behaves dynamically like a damped harmonic oscillator (Hatzes *et al.* 1991) with period T. To first order, the contact time in low-speed collisions is $t_i = T/2$, independent of impact speed. In this regime, the impact force $F_I \propto v_n$. We expect the interpenetration of the frost layers to be proportional to F_I and the corresponding sticking force F_s to be proportional to the penetration depth when it is small. Thus $F_s \propto v_n$ in such a model for low impact speeds.

In Fig. 3, the values of F_s and the critical speed above which sticking ceases are significantly higher than those found by Hatzes *et al.* (1991) ($F_s \lesssim 100$ dyn; $v_{\rm crit} \approx 0.07$ cm sec^{-1}). We have observed sticking forces up to 1500 dyn and critical impact speeds of 0.3–0.4 cm sec^{-1}. The

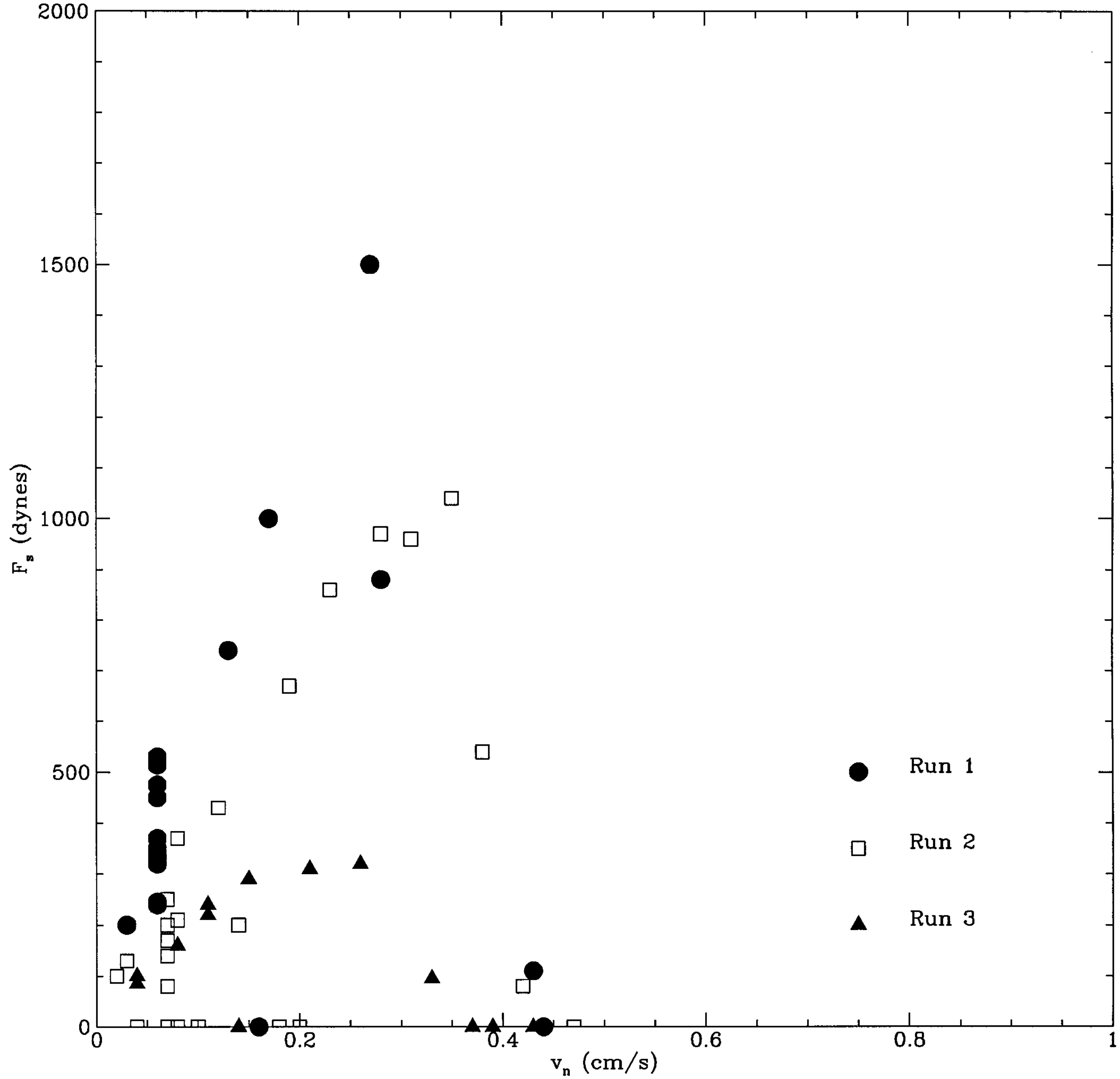

FIG. 3. Sticking force F_s (dyn) as a function of radial impact velocity v_n (cm sec^{-1}) for water-frost-coated ice surfaces. The three different symbols represent three different frosting runs (see text).

frost in these recent experiments probably has a different physical structure; a less fragile frost layer would be expected to stick more strongly and to stick at higher speeds as well. The differences in these results emphasize the fact that the physical structure of the frost is critical in determining its sticking properties.

The above results for water ice and frost can probably be generalized to other types of surface layers. Surfaces coated with frosts or with a layer of micron-sized particles can provide a mechanism for large energy losses in collisions. The measurements of Blum and others (Blum and Münch 1993, Blum 1990, Pinter *et al.* 1989) clearly show significant energy losses and some sticking for a different temperature regime, and Hartmann (1978) showed that ε is greatly reduced by the presence of a surface layer of rock powder on a clean rock target. We have also carried out collision experiments using a CO_2 frost layer instead of water frost. The results for ε as a function of impact speed are shown in Fig. 4 for various temperatures. The energy loss in low-velocity collisions is comparable to that for the water-frost-coated particles, but the temperature variation is more pronounced, most likely because CO_2

sublimates at a much lower temperature. The magnitude of ε for the CO_2 frost is low, even for very slow collision speeds, when the temperature, T, exceeds 150 K. (Note that for $T > 150$ K, CO_2 frost sublimates quickly, and a layer of surface frost disappears in a few hours.) Sticking in low-velocity collisions is also not limited to the water-frost-coated particles in our experiments. In a few measurements with CO_2 frost, we have obtained sticking forces in the range 10–20 dyn (for an $\sim$1 mm^2 contact area). Although these forces are somewhat smaller than for water frost, it is not yet clear whether or not higher sticking forces could be achieved. It may well depend on the structure of the frost that has formed. Further measurements on a series of different frosts are planned.

In initial static sticking experiments using methanol (CH_3OH) frost, we have observed sticking forces above $\sim$200,000 dyn (the measurement limit of our apparatus) over a much larger contact area (0.78 cm^2). These experiments were conducted in a different apparatus from that used in the experiments discussed previously (see Bridges

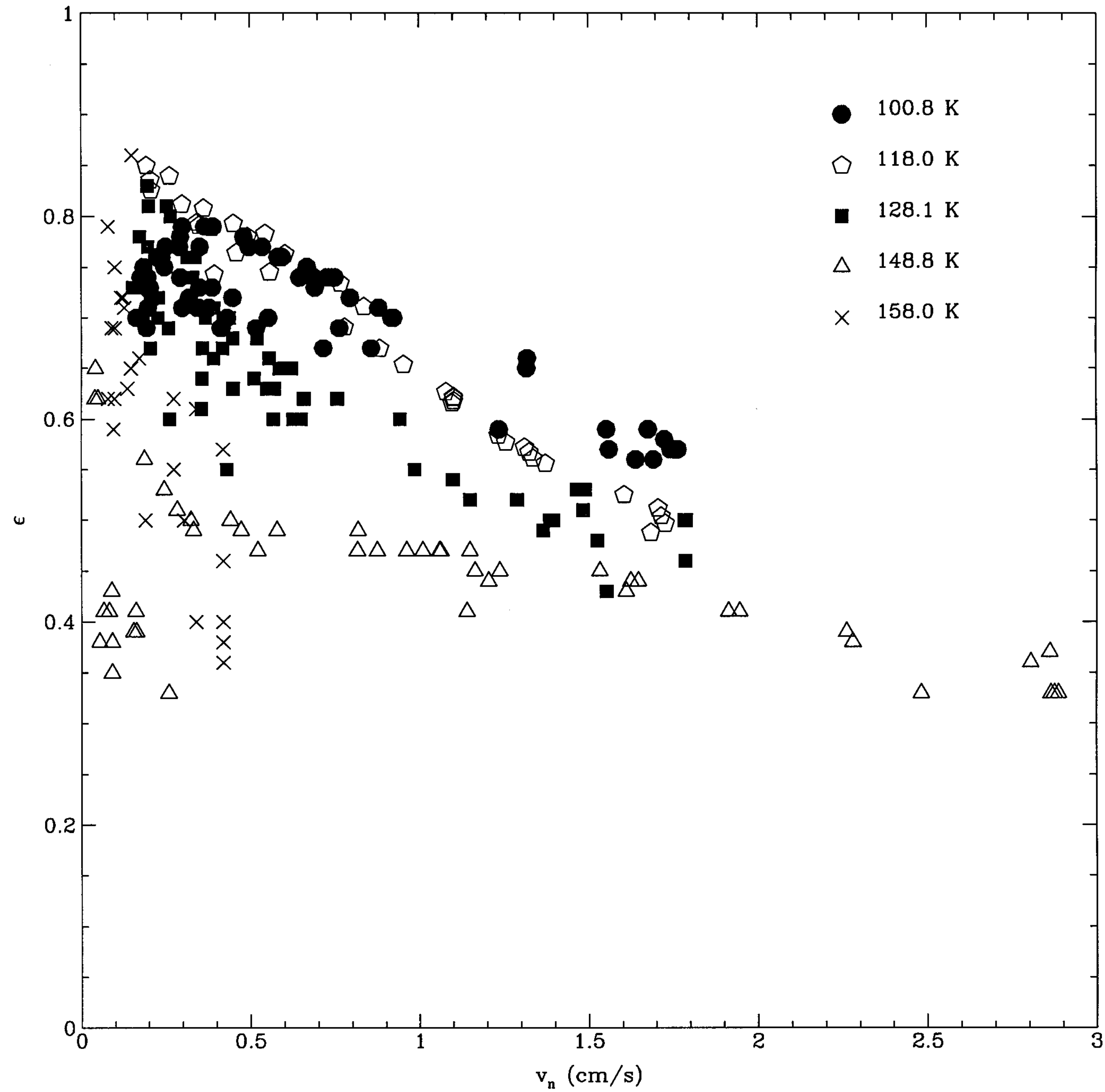

FIG. 4. Coefficient of restitution as a function of radial impact velocity for several experimental runs at various temperatures using a sphere and flat surface made of water ice, both coated with CO_2 frost.

et al. 1996 for a complete description). This apparatus does not involve two particles colliding, but instead compresses two frost-coated flat surfaces together; it is thus a static sticking experiment rather than a dynamic one. It is clear from these results that methanol is another volatile that can produce frosts which stick together effectively. In the outer solar nebula, admixtures of methanol and the much more abundant H_2O may create frosts which possess higher sticking forces than those we have measured for pure H_2O.

3. APPLICATIONS TO PLANETESIMAL FORMATION

3.1. General Considerations

Our measurements, as well as those of Blum and Münch (1993), suggest that in the absence of a surface layer that promotes sticking, small, hard, cool particles will not aggregate but will continue to collide nearly elastically, similar to molecules in a real gas. When the collision speed is low enough that fracturing and/or plastic flow does not occur, the particle surface is compressed nearly adiabatically (i.e., like a spring), and the energy lost to internal sound waves is very small. The range of impact speeds for which ε remains close to unity clearly varies with the strength of the material, but even water ice (at low temperatures) is very elastic at velocities below 1 cm sec^{-1}. For silicates, the range of speed for elastic response will be much larger.

The presence of a surface layer of microscopic, frost-like particles changes the dynamic behavior in two important ways: it enhances the energy loss in collisions and in some cases provides a mechanism for cohesive particle aggregation through mechanical interlocking of the surface layers. Such frosty surface layers can be formed by: (1) direct condensation of molecules to form frost; (2) aggregation of a layer of frost-coated dust particles as a larger particle sweeps through a cloud of micron-sized particles; and (3) as a consequence of sublimation in a low-pressure environment. Direct condensation requires a vapor of atoms to be present over relatively long times. An obvious candidate is water vapor, but frosts of other materials such as CH_3OH, CO_2, CO, NH_4, and N_2 will also play a role at low temperatures. The surface frost could form directly on the surface of the large particle; however, it is more likely that tiny "snowflakes" nucleate on dust particles in the nebular gas and are subsequently deposited on the surfaces of the larger particles by process (2) above. These two mechanisms for frost formation are probably not equivalent in terms of the properties of the resulting surface layers. In our measurements, both energy loss and the possibility of sticking are enhanced if the surface layer is porous. The morphology of the surface clearly depends on the growth mechanism; the surface frost will probably be more porous if it is formed by the aggregation of small, frosty dust-like particles rather than by deposition of individual molecules. In addition, if the temperatures within the outer regions of the solar nebula were much higher than 200 K in some epochs, other types of "frosts," formed of less volatile materials, might also be important if they resulted in porous, fragile surface layers. However, we think that for the outer reaches of the primordial solar system, only the frost layers formed from more volatile compounds are important.

A layer of tiny dust-like particles that has not been compacted will provide a significant energy loss mechanism for removing the relative kinetic energy from a collection of particles. All types of dust material, from the ice grains studied here to silicate powders (Hartmann 1978), should be effective; thus, this energy loss mechanism should operate in both the inner and the outer solar nebula. The surface layer also diminishes the impact forces by increasing the duration of the collision; the thicker the layer, the more energy that can be absorbed in a collision and the longer the duration of the contact. Both appear crucial for removing relative kinetic energy and minimizing impact forces prior to the formation of stable aggregates in the centimeter to kilometer size range. The reduction of relative velocities is a necessary prerequisite for aggregation via contact sticking using the magnitude of sticking forces measured to date.

Dust particles can be formed copiously in a few hard high-speed collisions or directly via condensation from the gas phase, or can be left over from previous epochs. If these tiny particles have regular surfaces, it appears unlikely, from our measurements, that they will contribute significantly to cohesive aggregation. In the limited data we have collected, sticking has been observed only when the surface layers of the colliding particles are highly irregular and can interpenetrate into one another. Thus, for aggregation, the shape of the microscopic surface particles, and, consequently, the conditions under which they formed, may be a crucial, but as yet neglected, aspect of planetesimal formation.

For the more volatile materials, including H_2O, sublimation is very important. At temperatures as low as 150–200 K, water ice surfaces sublimate appreciably at low ambient pressures. We have used this feature to remove thin surface layers of water frost. At somewhat lower temperatures (100 K), the sublimation rate is so low that no loss of material was observed, consistent with the sublimation temperature of water ($T = 152$ K) tabulated by Yamamoto (1985). Thus, the conditions under which micron-sized ice particles are present may be tightly constrained. Such particles may exist only in those regions of the nebula which satisfy at least one of the following criteria: (1) the temperature is high enough ($T > 150$ K) that a significant vapor pressure of water molecules is present which could condense if the temperature decreases; (2) the temperature is low enough that the vaporization of the existing frost particles through sublimation is not important; or (3) another mechanism to produce new frost particles is operating. Sublimation of volatile species is also an important issue in the development of the outer-planet satellites as discussed by Lunine and Tittemore (1993).

In environments sufficiently warm that material can sublimate slowly (such as water ice at 160 K), the surface of a large particle will roughen nonuniformly, providing yet another means of forming a lossy surface layer. Solid materials are typically polycrystalline; since different crystal facets sublimate at different rates, the surface region becomes porous with a fine lattice of bridging networks. In subsequent collisions, this porous surface is crushed, leading to a surface layer of powder. (The coefficient of restitution for such a layer is very similar to that for a frosted layer in the case of water frost (Hatzes *et al.* 1991).) Similar considerations must also be applied to other constituent particles of the solar nebula.

Possibly the most important property of a porous, irregular, frost-like surface is that it provides a sticking mechanism, with sticking forces for water frost of order 100–1000 dyn for a contact area of $\sim 1\ \mathrm{mm}^2$ when the impact speed is sufficiently low. The results for CO_2 frosts are comparable, although considerably lower. Methanol also provides a frost surface that sticks upon contact, with sticking forces that can be much larger than for either H_2O or CO_2 frost. We have pointed out (Hatzes *et al.* 1991) that composite aggregates made up of many small particles with a 100-dyn sticking force at each point of contact can be relatively stable, even in a moderate gravitational tidal force such as exists in the rings of Saturn. The smaller the particles making up the composite, the stronger the binding forces (because there are more contact areas per volume). Such objects are also more stable against breakup from impact forces. Glancing collisions may dislodge small particles on the surface, but the fraction of collisions that hit the aggregate with nearly grazing incidence is small. An aggregate made up of many small hard objects (0.1–10 cm) bound together by layers of surface frost may be a realization of the DEBs (Dynamic Ephemeral Bodies) proposed some years ago by Weidenschilling *et al.* (1984).

3.2. Elements of a More Realistic Planetesimal Formation Model

Many investigators have addressed particular aspects of planetary formation, but always with major simplifications to make the problem tractable. The resulting models are probably reasonable approximations for particular times in the evolution of the Solar System, but at other times the conditions change, "constants" do not remain constant, and the particular model is no longer applicable. Below we list some of the assumptions and working hypotheses that probably need to be included in more realistic models of planetesimal formation in the primordial solar nebula. These considerations apply to the cool outer solar nebula throughout its evolution and to the inner solar nebula during later stages, when the nebular gas has been depleted and the ambient temperature has decreased enough to allow frost formation. We then discuss a range of scenarios that are consistent with this set of constraints.

1. We assume, in agreement with Weidenschilling and Cuzzi (1993), that cohesive sticking must occur for particles in the centimeter to kilometer size range to aggregate.

2. For sticking to take place, the relative particle speed must be low, below some critical speed, and a sticking mechanism(s) must be operative. From the results outlined above, sticking is not easy to achieve, and deformable interpenetrating surface layers appear to be a necessary although not sufficient requirement. We propose that, in the cooler outer regions of the solar nebula, the sticking layer is composed of frosts of the volatile components.

3. We assume that the average temperatures, T, are <300 K for distances greater than 1 AU, consistent with the estimates of Hayashi (1981). T is probably lower than 30 K at much larger radial distances (>80 AU). It is unlikely that the change of T with time for a region of the nebula was monotonic. Within the flattened disk, T decreases away from the central plane region, and convective motion through the plane would lead to cyclic variations in T. For noncircular orbits, radiative heating would also vary cyclically with the orbital period.

4. The volatile materials in the primordial solar nebula that would form frosts for $T \ll 300$ K include H_2O, CO_2, CH_3OH, CH_4, CO, and N_2. Water occurs in many regions of the solar system and has a sublimation temperature, T_s, near 150 K in the radiative equilibrium model of Yamamoto (1985). Water frost can nucleate on microscopic grains over a wide range of temperatures, depending on the ambient water vapor pressure. The other reasonably abundant volatiles should behave similarly, but all of them have lower sublimation temperatures. The lowest sublimation temperature is $T_s = 22$ K for N_2 (Yamamoto 1985). Thus, these volatiles can provide a porous surface frost layer over a rather wide range in ambient temperature.

5. Models of the nebular gas dynamics and the coupling between planetesimals and the gas indicate that in many phases of its evolution the nebula was a turbulent, violent place. Some models show that in regions of more laminar flow the relative velocities can be quite low; Weidenschilling and Cuzzi (1993) show plots in which the relative velocities are in the range of 1–$1000\ \mathrm{cm\ sec^{-1}}$. These velocities are the result of thermal motions as well as Keplerian motion plus drag interactions with the nebular gas. Particles of the same size have a relatively small velocity dispersion, but particles of different sizes have the above range of relative speeds. For the relatively weak sticking forces

that we have observed to date for H_2O and CO_2 frosts, this range of speeds is still a little too high to achieve sticking in a collision. Additional energy damping is necessary if sticking via frost layers of these materials is to be an important mechanism for particles of different sizes. The larger sticking forces observed recently for CH_3OH frost may relax this requirement.

6. The formation of comets, assuming that it occurred within the Solar System, should have been very similar to the formation of some of the planetesimals. The composition of volatiles in comets suggests that the formation of these objects occurred at $T < 60$ K, which probably corresponds to distances greater than 20 AU from the Sun (Mumma *et al.* 1993), i.e., the region of the outer planets. The various models developed for the structure of cometary nuclei are likely relevant for the formation of small planetesimals; the icy-glue (Gombosi and Houpis 1986) and icy-conglomerate (Whipple 1950) models appear most appealing.

7. Weakly bound aggregates need to be compressed, or the particle–particle bonding forces need to be increased, to produce stable planetesimals. This could be achieved through periodic heating and by hard collisions in which some material is compressed and some is ejected.

The above list places considerable constraints on the formation of planetesimals. In the micron to a few centimeter size range, porous or fractal-like objects (Donn *et al.* 1985) might have formed; Donn (1990) has suggested that in collisions these small uncompacted objects would interpenetrate and thereby agglomerate. Important objects of this nature are extended, porous frost particles, formed of the constituent volatiles, which may be up to several millimeters in size. The local density of such frost particles will depend on the density of dust particles which act as nucleation sites, as well as on the temperature and the amount of volatiles present in the nebular gas. Temperature plays a very important role, as the vapor pressure varies exponentially with T; consequently, with modest changes in the ambient temperature, the size and density of frost particles can change considerably.

For the development of larger planetesimals ($\geqslant$1 cm) from bodies a few centimeters in size, a mechanism that results in the cohesion of hard objects is required. We propose that layers of porous frost, formed of various volatile materials, provide such a mechanism for sticking. The frost could form directly by condensation of the nebular gas on the surface of a large particle. However, that process may form a dense layer, similar to the dense frost that we have made in the laboratory; such compact frost layers do not stick. A more important possibility is that micron-sized frost particles, discussed above, form a porous layer on larger planetesimals. Our experiments indicate that moderate sticking forces are possible, on the order of 100–1000 dyn over 1 mm^2. If the particles composing an aggregate are small or if the area of contact is large, the net sticking forces holding an aggregate together can be significant, much larger than the local gravitational and tidal forces.

Aggregation of small planetesimals has been modeled by many investigators (see Weidenschilling and Cuzzi 1993, Lissauer and Stewart 1993, Ohtsuki *et al.* 1993 for recent reviews) using various assumptions about the densities and masses of the constituent particles. However, little theoretical attention has been given to the specific mechanism for the adhesion of particles; instead, a sticking probability is usually assumed in these models. It is recognized that the random velocities must be damped out. An average value of the coefficient of restitution is often used to model energy loss, but the details of the collisions and the evolution of the particle surfaces are ignored. Such models are reasonably tractable and provide useful insights into some aspects of planetesimal formation, but even for these simplified models, numerical solutions are not straightforward (Lissauer and Stewart 1993). The models are still too simple to provide a realistic model of aggregation, however. Relatively small variations in the ambient particle surface temperatures can cause a volatile component to sublimate or recondense. Thus, the sticking probability could be aperiodically turned on and off when the average temperature is close to the sublimation temperature of one of the volatile components. The sublimation–recondensation process continually reforms new frost particles; this reprocessing of frost particles appears to be a necessary condition for sticking to occur (in all our measurements, compacted frost layers do not stick). In addition, the rapid formation of fluffy frost layers introduces an extremely efficient energy damping mechanism in which more than 95% of the relative energy can be lost in each collision ($\varepsilon = 0.2$ removes 96% of the relative kinetic energy in one collision). This mechanism is also turned on and off as the frost layer sublimates and reforms; the energy loss will be highest at the same time that the sticking forces should be largest.

Composites formed through the sticking of frosted surfaces may be stable on a short time scale, but they are still weakly bound together and are thus susceptible to breakup in hard collisions with other large objects. Relative velocities between particles of different sizes in a turbulent solar nebula are significant (Weidenschilling and Cuzzi 1993), and could disrupt aggregates held together only by low-temperature frost sticking forces. There are several processes which can result in a significant increase in the sticking force between composites which are initially held together weakly. Models of solar nebula structure (Lin and Papaloizou 1985; Ruden and Lin 1986) indicate a large temperature gradient in the direction normal to the plane of the disk. Turbulent motion, driven by convective instabilities, can induce Brownian motion and random walk among composites (Weidenschilling 1984, Morfill and Völk

1984). Over long periods of time (and if the ambient temperature is sufficiently high), sublimation and recondensation or diffusion within the contact region could strengthen the interparticle bond. If there are significant temperature fluctuations (for example, if aggregates move cyclically through regions of higher temperatures), a phase transition could result in much stronger bonds. For example, consider the motion of an ice aggregate at a radial distance of several AU in the solar nebula. As it undergoes random walk between the midplane and surface layers of the nebula, the ambient temperature of the gas may vary by a factor of two (Ruden and Lin 1986). A layer of amorphous water frost may be deposited when the aggregate is near the surface of the solar nebula where the temperature is less than 100 K. As the aggregate moves through the midplane where the temperature may increase above 140 K, the amorphous frost layer could undergo a phase change to cubic-lattice ice. Thus, a collection of particles held together initially by amorphous water frost may become quite rigid if the interpenetrating frost layers convert to the cubic crystalline state upon warming. For other types of frost or different ambient temperatures, other phase changes may strengthen the bonding. Another possibility is that large aggregates may occasionally collide at high impact speeds. This will vaporize the frosty material, providing vapor to produce new frost layers and compress some of the nonvolatile components, occasionally resulting in larger hard objects.

4. CONCLUSIONS

We have outlined some of the problems that exist for the formation of large cool objects by aggregation within clouds of dust or small particles. The necessary conditions for aggregation must include some mechanisms to reduce the relative kinetic energy, to minimize the impact forces by constraining the collisions to be "soft," and, for small objects, to provide a surface-sticking force when impact speeds are low enough. Electrostatic forces can provide bonding at micron sizes, while self-gravity becomes very important when objects are ~100 km in diameter. Neither of these mechanisms is effective in the centimeter to 100-m size range.

Our studies of the collisions of water ice particles, with (and without) a layer of H_2O or CO_2 frost present, show that when frost is present, the impacts are soft and the energy loss per collision can be high. Further, when the impact speed is low (for water frost, <0.4 cm sec^{-1}) and the frost is not compacted, the mechanical interpenetration of the frost layers at contact provides a significant sticking force. Preliminary results indicate that methanol frost creates an even stronger bond than H_2O or CO_2. We point out that the presence of surface frosts is strongly temperature dependent and that for particular conditions, frosty layers could have reformed rapidly, providing fluffy surface frosts that would promote aggregation.

We have generalized these results to the frosts of other volatiles and proposed that surface layers of frost are an important intermediate step in the formation of large particles in the outer solar nebula. We have also suggested several ways in which composite particles, initially formed by the sticking of frosted surfaces in very-low-speed collisions, may become much more rigid and thus able to survive high-speed collisions with other aggregates in the turbulent solar nebula environment and to provide the building blocks for planetesimal formation.

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