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STICKY ICE GRAINS AID PLANET FORMATION: UNUSUAL PROPERTIES OF CRYOGENIC WATER ICE

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ABSTRACT

There is limited time for the dust in the nebula around a newborn star to form planetesimals: in a few million years or less the star's stellar winds will disperse most of the unagglomerated dust. It has been difficult to explain the efficiency by which dust grains must have agglomerated to form planetesimals in circumstellar disks. A major obstacle is the fragility of aggregates, leading to collisional fragmentation, which makes it difficult for them to grow to, and beyond, meter-sized bodies. The distinct properties of cryogenic (5–100 K) amorphous water ice, which composes or coats the grains in the cooler parts of the nebulae ($\gtrsim$Jovian distances), may be able to account for the rapid agglomeration. Measurements are presented that show that this ice readily acquires persistent macroscopic electric dipoles, strongly enhancing grain-grain adhesion. In addition, measurements were made showing that vapor-deposited amorphous water ice is also highly mechanically inelastic ($\approx$10% rebound). Together these may explain this efficient net sticking and net growth. Similar properties of higher temperature grains may aid agglomeration in the inner regions of the nebulae.

Subject headings: astrochemistry — dust, extinction — molecular processes

1. INTRODUCTION

Dusty nebulae around a new star will, in around 1 million yr, be stripped of that dust by the outward stellar wind (Briceño et al. 2001). If planets are to form, their kilometer-sized progenitors must accrete in this time frame. Models of this process show that, once formed, gravitationally bound planetesimals (>1 km or so) will grow quickly, but the theories invoking only van der Waals forces do not predict a net rate of agglomeration of the micron-sized dust and its agglomerates fast enough to eventually form planetesimals (Ossenkopf 1993). The agglomeration rate of micron-sized dust grains depends on their collision rate and any long-range forces that would increase that rate, their collisional inelasticity, and the adhesive forces that could stabilize the new assembly (Bridges et al. 1996) and prevent fragmentation as it grows larger. Van der Waals interactions alone make for fragile agglomerates that do not survive collisions well. Longer range electrostatic forces have been proposed by some authors to be important factors for the agglomeration. Poppe et al. proposed that charge exchange between colliding grains can make the grains stick (Poppe & Blum 1997; Poppe et al. 1999). Marshall & Cuzzi (2001) proposed that the grains must have a large net dipole. The dipole-dipole interaction would cause faster aggregation and higher resistance to aggregate shattering (Marshall & Cuzzi 2001; Abrahamson & Marshall 2002), but it was unclear how such a large dipole could form (Poppe & Blum 1997; Poppe et al. 1999; Marshall & Cuzzi 2001; Blum et al. 2000).

The agglomeration rate of two individual micron-sized grains and the agglomeration rate for clumps containing several millions of grains span a range of dominant issues and unknowns. Models have problems throughout this range predicting appropriate net growth rates (including the effects of shattering) unless the forces present between grains are in considerable excess of what simple van der Waals forces would predict and unless the inelasticity/sticking probabilities are very high. While these stronger forces and stabilities apparently do exist in a few microgravity and 1g experiments for the particular refractory particles chosen (Abrahamson & Marshall 2002; Blum & Wurm 2000; Krause & Blum 2004), a physical explanation of the mechanism has been rather elusive for these experimental surrogates, and it is not clear that one can generalize this conclusion to include real nebular materials. The work here suggests that the properties of low-temperature water ices can provide the physical mechanisms in the cold regions of planetary nebulae to account for the increased agglomeration rates and agglomerate stability.

Condensable molecular materials, particularly water, are abundant in protoplanetary systems (Fraser et al. 2002). Below 120 K, ice condenses from the gas phase to form amorphous ice (not crystalline) (Petrenko & Whitworth 2002, p. 277). The temperature in the cooler portions of the solar nebula is well below 100 K (Willacy et al. 1998), and comets and giant planets (such as Jupiter) appear to have formed below 30 K (Crovisier et al. 1997; Owen et al. 1999; Kawakita et al. 2001), so ice will exist in the amorphous phase in these regions. It has been shown that amorphous ice will have very different properties depending on the deposition temperature (Mayer & Pletzer 1986; Brown et al. 1996). When deposited near 120 K, it is compact, with a density near that of crystalline ice, but as the temperature of growth drops, it becomes fluffy on a molecular scale, with a density near 0.6 g cm^{-3}. Both of these references focused on the enhanced uptake of gases possible as a result of microporosity, and Mayer & Pletzer also discussed some of the astrophysical implications of this enhanced uptake (H-atom recombination). In addition, a few studies have explored whether low-temperature ices might have unique properties relevant to low-velocity collisions (Bridges et al. 1996; Higa et al. 1996; Hessinger et al. 1996; Supulver et al. 1997). However, prior elasticity studies were typically performed at too high a temperature (>100 K) to see the most inelastic regimes. Hessinger et al. (1996) did infer from vibrating paddle measurements of the shear modulus and internal friction of thin films that water ice

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grown at low temperature ($T = 48$ K) may be very inelastic in nebular-type collisions. Ehrenfreund et al. (2003) discuss the effects of water ice in agglomeration, and many of the yet unanswered questions, in a review that also highlights their planned *International Space Station* water-ice microgravity agglomeration experiments. We provide new evidence that at these very low temperatures, amorphous water ices have electrical and mechanical properties distinctly different from crystalline water ice and that this should lead to enhanced agglomeration of icy grains. Most of the experimental data shown here are being published for the first time. Some have appeared earlier (Fig. 1, *circles*; Iedema et al. 1998) but were not applied to the issues of planet formation.

2. ELECTROSTATIC PROPERTIES OF ICE

Little attention has been given to low-temperature ice's unique electrostatic properties, which might influence the aggregation of ice grains. Water molecules, which have molecular dipoles of several debye, have a nearly perfect balance of "up" and "down" dipoles in normal high-temperature ice, with no net polarization. However, it has been shown that water ice formed by vapor deposition on cold substrates (<165 K) becomes spontaneously polarized via partial alignment of the water molecules (the ferroelectric-like or "electret" effect; Kutzner 1972; Onsager et al. 1978; Iedema et al. 1998). The asymmetry of the ice-vacuum interface causes very low temperature vapor-deposited ices formed from most polar gases to adopt a net polarization, for which a net orientation of up to a few percent of the molecular dipoles occurs. This and other electrical properties (ferro- and piezoelectricity) we have characterized may have important implications for planetesimal formation.

2.1. *Measurement of Spontaneous Dipoles in Ice*

The ferroelectricity of low-temperature ice was measured on films using a Kelvin contact potential difference probe (Iedema et al. 1998). This determined the voltage difference across the film ("film voltage"). The experiments were done in an ultrahigh vacuum chamber with a base pressure of 2×10^{-10} torr. Briefly, the ice films were grown on a Pt(111) crystal substrate using a molecular beam, directed tube dosing, or background dosing. The collimated normal incidence of the molecular beam tended to form compact amorphous ice below 120 K and crystalline ice above this temperature (Brown et al. 1996). Water was dosed by the molecular beam at various substrate temperatures at about 0.15–0.2 monolayers s^{-1}. Tube dosing or background dosing formed a nanoscale fluffy ice layer at low temperature. The surface coverage was determined by the temperature of the peak desorption rate during temperature-programmed desorption of the water (Iedema et al. 1998). Background dosing was done by leaking water vapor into the chamber through a leak valve while the temperature of the Pt substrate was maintained below 35 K. The pressure inside the chamber was kept around 9.4×10^{-7} torr for 105 minutes. The coverage of the ice film created by background dosing estimated from the pressure and water sticking probability was in good agreement with that estimated from the temperature-programmed desorption peak temperature.

Figure 1 shows the negative voltage generated across a water ice film (created by the ferroelectric effect) versus the film thickness for the molecular beam–grown film at 31 K (for convenience, the density of the amorphous ice has been assumed to be 0.7 g cm^{-3}; Tsekouras et al. 1998). The voltage is strictly linear with thickness. A 6.7 μm film generates over 200 V at 31 K. A linear fit of the data results in a slope of 33 V μm^{-1}, which implies a net dipole along the surface normal of 3.7×10^{-3} D $molecule^{-1}$. As shown in Figure 1, a 2.24 μm (5000 monolayer) film created by background dosing at 35 K leads to a film voltage of about 2.3 V μm^{-1}. This corresponds to a net 2.6×10^{-4} D $molecule^{-1}$, 7% of the value for the ice films created by normal-incidence molecular-beam dosing. Also shown in Figure 1 are data from Iedema et al. (1998; tube dosed), which is similar to that measured in this work using the molecular beam. The results show that micron-thick ice deposits should develop tens to hundreds of volts of electrostatic potential for deposition temperatures less than 100 K. When the ice deposition temperature increases, the ferroelectricity decreases dramatically. For an ice film created at 120 K by molecular-beam dosing, the film voltage is only 0.31 V μm^{-1}. Thus, ferroelectricity is favored at low temperature.

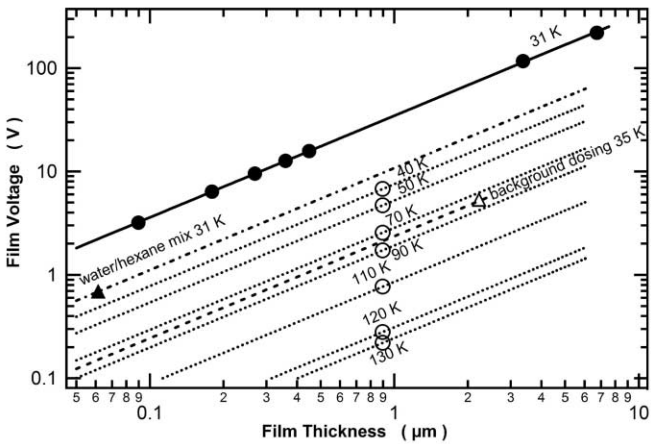

FIG. 1.—Film voltage of amorphous ice as a function of thickness. The filled circles are from this work and are for films created by molecular-beam dosing at 31 K. The open circles are from semidirected tube dosing at 35 K (Iedema et al. 1998). The slope of the fitted solid line for the data at 31 K is 0.984 decades $decade^{-1}$, which shows an essentially linear dependence of voltage with coverage, at 33 V μm^{-1}. Dashed curves have unity slope. The filled triangle shows the measured voltage for a 50% water/hexane mix, and the open triangle is for background dosing at 35 K.

However, the ice in nebulae is not always so pure. Does impure ice also show this voltage growth? Other volatile molecules found in interstellar or cometary ices are predominantly CO, CO_2, CH_4, CH_3OH, and NH_3 (Fraser et al. 2002). CO_2, CH_3OH, and NH_3 are dipolar and show considerable dipolar alignment (similar to or greater than that for water) during vapor deposition in the pure form (Kutzner 1972). We have not studied these mixed with water ice, but we did look at a "generic" nominally nonpolar hydrocarbon hexane, mixed at about 50% mole fraction with water. The results, shown in Figure 1, demonstrate that dipole alignment occurs even for this "dirty ice."

A symmetrically coated (with aligned water ice) grain in a nebula will have a center region positively biased with respect to the outside but no net dipole (Fig. 2, *top middle*). If the core of the grain is *very* asymmetric or has some other asymmetric history, then it will have a net dipole. Collisions with other grains will also create a dipole. As shown in Figure 2 (*top*), an icy particle with no initial net dipole can fragment on collision or simply depolarize on one side, creating a net dipole (judging from temperature studies, the polarization of amorphous ice is likely very collisionally fragile; Tsekouras et al. 1998).

2.2. *Estimated Magnitude of the Dipole Moment*

For simplicity we assume that the grains are roughly spherical and are totally made of ice. We assume the density of the fluffy amorphous ice to be 0.7 g cm^{-3} (Tsekouras et al. 1998),

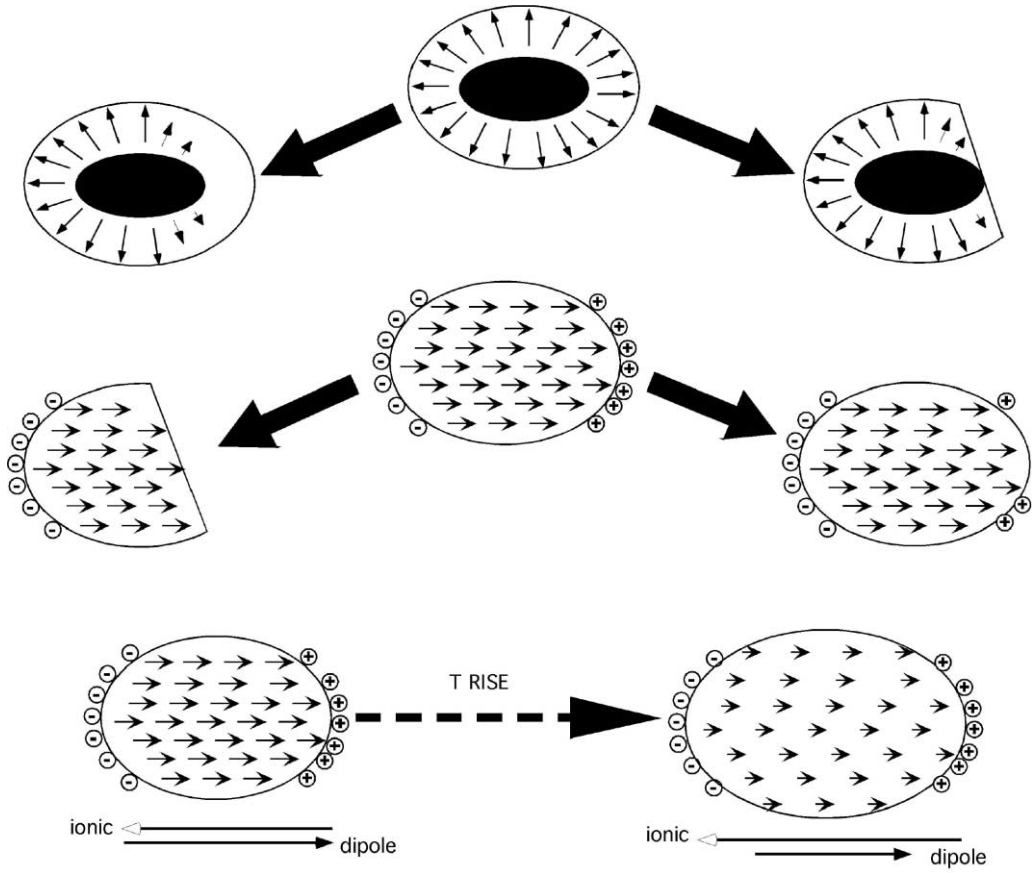

FIG. 2.—Development of grain dipoles. The grains acquire or recover a net dipole for a variety of reasons: The top middle shows a mineral grain with a uniform coating of aligned ice, with no net dipole. A collision can fracture it (*top right*) to create a net dipole or simply partially depolarize it (*top left*). The middle shows a grain whose original net dipole is shielded by adsorbed charges. Collisions can unmask the dipole by fractures (*middle left*) or by surface charge transfer (*middle right*). The bottom shows how a temperature change can unmask the dipole, via the pyroelectric effect.

grown at 35 K. The total dipole moment associated with each grain can reach a maximum value of $P_T = pN$, where N is the total number of the water molecules in one grain and p is the dipole moment contributed by each water molecule to the ferroelectricity (or film voltage). For a 2 μm diameter particle, N is 9.8×10^{10} molecules. If we take $p = 2.6 \times 10^{-4}$ D molecule^{-1} (the value obtained from background dosing at 35 K), P_T is about 8.6×10^{-23} C m or 2.6×10^{-2} GD. This number is roughly equal to putting about 270 positive charges on one end of the grain and 270 negative charges on the other end. The dipole-dipole interaction between two such icy particles is $P_T^2/(2\pi\epsilon_0 d^3) = 1.7 \times 10^{-17}$ J (see Table 1). This interaction is 5 orders higher than their thermal energy (4.1×10^{-22} J) at 30 K. A 400 μm diameter ice grain could have as much as 2.1×10^5 GD. In their analysis of the high rate of agglomeration observed for silica dust under microgravity conditions, Blum et al. (2000) considered dipole interactions, but at that time, their a priori estimate of the expected grain dipole (with a 0.95 μm radius) was only 2.3×10^{-4} GD, and the corresponding dipole-dipole interaction energy (see Table 1) was thus too small to be important. They based this dipole on an estimated upper limit of two to three elementary charges per monomer grain, but Marshall & Cuzzi (2001) took the approach of asking how big a dipole was needed to account for the observed agglomeration rate of 400 μm particles, estimating 100,000–200,000 GD. This makes for a predicted dipole-dipole interaction that is 3 orders of magnitude larger than the estimated van der Waals interaction and similar to our estimate for the water ice grain of the same size (see Table 1).

Dominik & Nübold (2002) pointed out that when the magnetic dipole-dipole interaction for micron-sized magnetic particles at 100 K is about 5 orders higher than random thermal energy, the agglomeration of magnetic grains is dominated by magnetic forces and the aggregate will be stable against thermal agitation. Similarly, the strong electrical dipole-dipole interaction in our case should accelerate icy grain aggregation (compared with having van der Waals forces alone) and should also greatly stabilize the newly formed agglomerates through the strong electrostatic interactions of the many particles making up the whole.

The grain dipole could be much less than the maximum given above, if it were nearly radially symmetric or thermally annealed, for example (Tsekouras et al. 1998). However, even a 1 or 2 order-of-magnitude reduction would still leave the residual dipole-dipole forces large enough to stabilize the agglomerates, especially for 10 μm grains or larger. However, ions and electrons in nebulae could strongly shield the external field of dipolar grains. Even in the dense dark nebular disk where stellar and cosmic radiation is negligible, the decay of radioactive elements would have resulted in significant ionization (Finocchi & Gail 1997).

2.3. *Shielding the Dipole in the Nebula*

The time required for the free charge to shield the grains' dipole can be estimated using the results of a nebular model that includes charges, such as that by Finochi & Gail (1997). Their model represents a nebula 10^5 yr after its birth, when grains should start agglomerating. We estimate the grain shielding time

TABLE 1
Comparison of Dipole-Dipole Interaction

Particle Diameter (μm)	Dipole (Prior Work) (GD)	Dipole Source (Prior Work)	Dipole (This Work) (GD)	Dipole-Dipole Interaction (Prior Work) (pJ)	Dipole-Dipole Interaction (This Work) (pJ)	van der Waals Interaction (pJ)
2.....	0.00023[a]	Estimated from equilibrium charge	0.026	1.5×10^{-9}[a]	0.000017	0.000015
400.....	150000 average[b]	Via expected agglomeration rate	210000	30–120[b]	133	0.0031

[a] Blum et al. 2000.
[b] Marshall & Cuzzi 2001.

via the rate of thermal collisions with the steady state ion/e^- density. Between 10 and 20 AU where the temperature varies from 70 to 20 K (Willacy et al. 1998), the main free charges in the region are electrons and S^+ (sulfur ions), whose densities n_c are about 400–800 cm^{-3} (Finocchi & Gail 1997). For the 2 μm diameter (=D) grain at 35 K mentioned above, about 270 positive (=Q_E) and 270 negative charges are required to shield the initial ferroelectric grain dipole. The time to neutralize should be roughly equal to or less than $Q_E/[(\pi D^2/4)n_c(kT/2\pi m_c)^{1/2}]$, where k, T, and m_c are the Boltzmann constant, ambient temperature, and the mass of the free charge (Horanyi & Goertz 1990) and $\pi D^2/4$ is the geometrical cross section of the grain. For $T =$ 30 K, this gives 0.3 minutes for electrons to shield the positive end and 70 minutes for S^+ ions to shield the negative end. These short times are consistent with the notion that ambient plasma densities ensure that grains will have a net charge number near zero (Ossenkopf 1993) and should also neutralize (shield) any dipole in the grain. If a large number of ice grains formed at once (as after a shock wave passes), the free charge could be depleted, and the ionization *rate* would need to be considered. If we assume that the ratio of solid material to gas in the nebula is that assumed as an initial condition by Weidenschilling (1997), 0.015, that all the solids are water ice of 2 μm diameter, and that the gas density (H_2) is about 1.6×10^{13} cm^{-3} (Finocchi & Gail 1997), the number of ice grains per cm^3 would be about 0.27. The positive or negative charge density associated with the icy grains would be 270×0.27 cm^{-3} $= 73$ cm^{-3}. This is comparable to the free charge density, so the ice grain dipole neutralization time might be dominated by the ionization rate. Using Finochi & Gail's (1997) ionization rate estimate near 15 AU, 3×10^{-18} s^{-1} per H atom, and the H_2 density given above, one can estimate that it would take about 9 days to generate enough new charges to shield the dipolar fields in this density of grain dipoles.

2.4. *Unmasking the Dipole*

The above calculations strongly suggest that any dipolar fields that might exist on icy grains would quickly become shielded, as they would collect external charges until the net dipole was near zero. This is depicted in the middle and bottom left of Figure 2. However, the shielded dipole can be "unmasked" by collisions or temperature change. A collision that fractures (or depolarizes) part of the grain, as shown in Figure 2 (*middle left*), will restore a large dipole, just in time to help the new fragments trap the colliding grains and their fragments through dipole-dipole (or dipole–induced-dipole) interactions.

Because the grain surface would need a substantial amount of adsorbed charge to shield a bulk dipole, contact-induced charge transfer is all the more likely. Ions at these low temperatures cannot migrate through the ice (Cowin et al. 1999). As shown in Figure 2 (*middle right*), another grain that hit the originally negative dipole end of the grain of a shielded dipole should have a propensity to transfer positive surface charge away; this would create two charged particles, both with large dipoles. This is similar to a model proposed by Pollock et al. (1995) in which a dipole is formed across a particle where two like-sign charge patches with unequal strength are at opposite sides of a colliding particle pair.

A third way exists to unmask the dipole: a change in temperature combined with ice's pyroelectric effect. Pyroelectricity is a voltage generated across a material when the temperature changes. This requires that the material lack an inversion center. While pure water ice has an inversion center, and thus zero pyroelectricity, the internally biased water grains shown in Figure 2 cause a net alignment of the molecular water dipoles in the grain. This destroys the inversion symmetry; thus, the ice can then have nonzero pyroelectric effects. The experimental arrangement employed in this study is nearly ideal for measuring water ice's pyroelectricity (which is being extensively characterized in an ongoing study). In an earlier study, this pyroelectric effect was measured and published (for crystalline water ice; Tsekouras et al. 1998). There, a 7800 monolayer thick water film with positive ions on top had a nearly zero external field at around 50 K (much like a shielded ice grain), but heating to 150 K regenerated 4 V across the film. In that study the pyroelectricity was measured, but the mechanism was not understood. The effect occurs because at temperatures below 140 K the water dipoles cannot flip, as shown in Figure 2 (*bottom*). The observed voltage is the difference between two large voltages: that from the ions and that from the oriented dipoles. Therefore, as the temperature changes from 50 to 100 K, the voltage across the grain due to the ions will increase as a result of thermal expansion and changes in the infinite-frequency dielectric constant (Mopsik & Broadhurst 1975). The water dipoles wiggle as a result of phonons, increasingly so as the temperatures increase. This decreases each molecule's average dipole, thus decreasing the voltage created by the net aligned dipoles. Each of these effects is only a percent or two for temperature changes of 100 K, but one increases, while the other decreases. The net result is that the particle regains a substantial dipole whenever the temperature changes.

Therefore, grain-grain collisions that chip shielded dipoles or transfer surface charge, or temperature changes induced by collisions or shock waves, can all partially restore the dipoles, making aggregation faster and aggregates more stable. When one has two *large* agglomerates that during a collision are at risk for fragmentation, the forces are particularly likely to "damage" the grains' amorphous ice/ion coatings. This will immediately create new dipolar forces that should stabilize the agglomerates, preventing fragmentation.

3. MECHANICAL INELASTICITY

In addition to its electrostatic properties, amorphous ice is known for being fluffy as a result of nanoporosity (Brown et al.

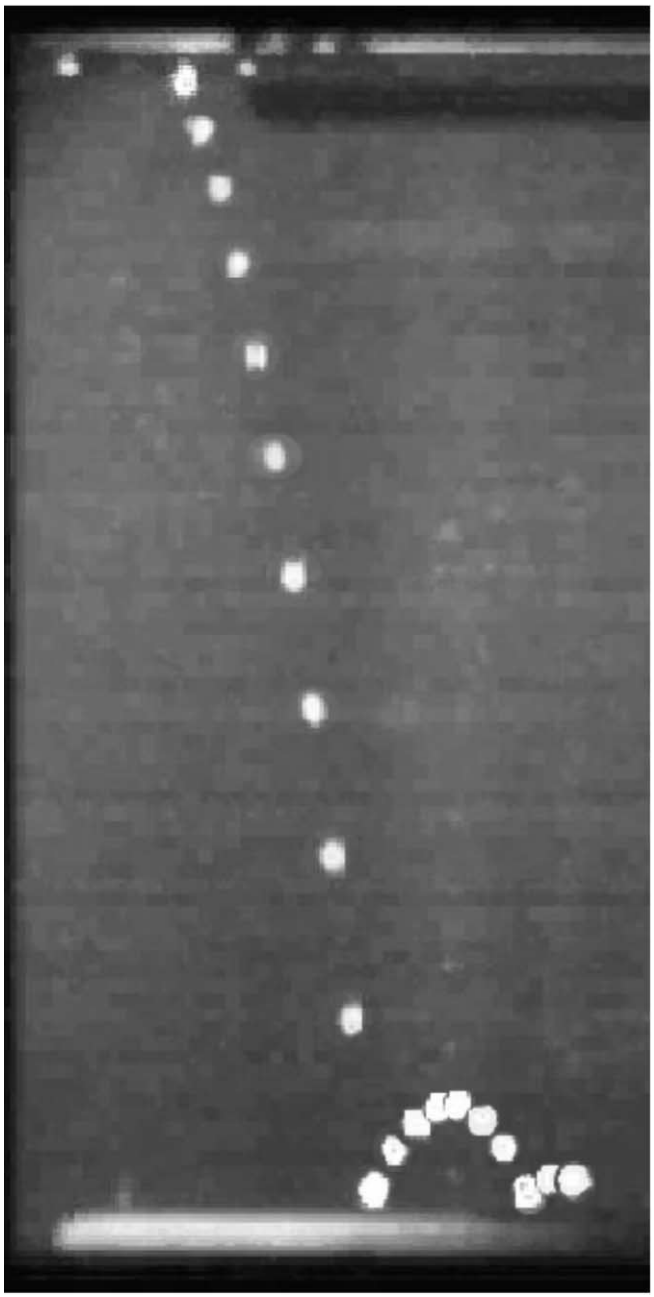

FIG. 3.—Rebound of ceramic ball on a thick amorphous ice film created at 40 K. The actual trajectory is nearly vertical: for better visibility each image of the ball is progressively shifted to the right.

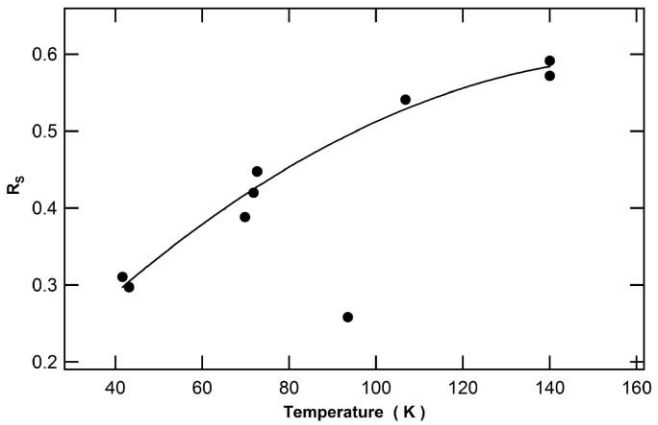

FIG. 4.—Restitution coefficients of a ceramic ball on amorphous ice films that were deposited at different temperatures. The deviation of the point at 93.5 K is most likely due to the fracture of the ice film.

1996), which may result in an intrinsic inelasticity in icy grain collisions. We performed a simple free-falling ball collision experiment (Higa et al. 1996) in a separate ultrahigh vacuum chamber to show that the morphology change of amorphous ice with temperature can greatly affect the sticking properties of the icy grains. A bare ceramic ball (3.2 mm in diameter, polycrystalline Al_2O_3) was placed in a copper stage 118 mm above a copper substrate. Both the copper stage and substrate were cooled using a closed-cycle He refrigerator.

The dosing was performed through a large, slotted, baffled can that closely reproduces "background dosing" uniformly over a several cm^2 region of the upper surface of the substrate. The can's slot was held 2 mm above the substrate to keep water vapor from degrading the chamber's high vacuum. The deposition rate was varied from 10 to 45 μm hr^{-1} (the films displayed no observable difference in their properties as a function of these dosing rates). After dosing, the ball was allowed to fall freely onto the ice-covered copper substrate. A high-speed camera (500 frames s^{-1}) was used to record the collision of the ball with the substrate (Fig. 3).

Ice formed at 40 K is highly amorphous, featureless, and opaque (white). The ball struck the surface with an approximate velocity of 1.5 m s^{-1}. The ceramic ball rebounded from the surface to an average of 9.6% of the original fall distance (and fairly reproducibly). This leads to a restitution coefficient R_s (the ratio of the ball speed after to that before the rebound) of about 0.31 at 42 K. A typical composite image of the ball drop is shown in Figure 3.

The restitution of ice, R_s, versus amorphous ice growth temperature is shown in Figure 4, with a continued rise to about 0.58 at 140 K. Above 140 K, a crystalline ice film formed that was transparent and compact. On crystalline ice the ball rebound was much more erratic, with R_s varying between 0.34 and 0.85 (data not shown). This impact velocity often induced fracturing of the crystalline ice film, similar to what has been observed elsewhere (Higa et al. 1996). The amorphous ice films did not appear to suffer from fracturing at this impact velocity. The R_s in the absence of fracturing should be near the highest value we observed, 0.85. This is close to that reported for crystalline ice (Higa et al. 1996).

Note that our method for preparing amorphous ice films is somewhat different from the methods used in other studies of the mechanical properties of amorphous ice. Here the ice was grown at very low temperatures, which is important for preserving its microporosity. Bridges et al. (1996), Supulver et al. (1997), and Higa et al. (1996) looked at ice grown at no colder than 100 K, which should produce mostly compact amorphous ice, not microporous (Brown et al. 1996). Hessinger et al. (1996) did grow ice at very low temperatures. However, their dosing arrangement had water evaporating from one plate held a distance away from the other substrate. In a liquid helium–cooled vessel this would have given line-of-sight dosing, which would be more like a normal-incidence molecular beam than true isotropic background pressure dosing. Normal-incidence dosing favors compact amorphous ice growth even at very low temperatures, so the state of that ice is ambiguous. Hessinger et al. (1996) did infer much higher inelasticities in their low-temperature ices compared to their higher temperature ices, so it was likely partially

microporous. Our low-temperature growth and true background dosing arrangement should have produced ice of maximal porosity.

4. DISCUSSIONS

Amorphous ice is found to be much more inelastic than crystalline ice, especially at temperatures well below 100 K. A more inelastic collision makes sticking of the grains much more likely than bouncing. This sticking will be further enhanced if we consider the dipolar forces that should be released on impact. Other means by which the dipoles are unmasked (contact-induced charge transfer and pyroelectricity due to thermal cycling) will likewise enhance attraction and agglomeration. Strong electrostatic interactions will also enhance the strength of the growing planetesimal against collisional annihilation. Given how much water ice exists in the outer portions of nebulae, and that these effects should exist for pure water ice grains, dirty ice, or ice-coated mineral grains, this provides a simple mechanism by which icy grains in nebulae could have had the increased sticking rate (unaccountable for by van der Waals forces alone) needed for planetesimal formation to have occurred in the relatively short time window before the new star blows away its surrounding nebula.

An agglomerate formed of dipoles will tend to develop a macroscopic dipole. This is concluded via calculations by Dominik & Nübold (2002), in the case of particles that have permanent magnetic dipoles as the major force between them. In their calculation, the agglomerate of N dipoles has a persistent dipole that is close to $N^{0.63}$ times the dipole of a single grain, as a result of the long-range field of the growing agglomerate aligning an incoming dipole. In microgravity experiments, Nübold et al. (2003) indeed found that magnetic particles agglomerate very rapidly, to form thread/web–like structures with presumably high net magnetic moments, in considerable (although not complete) agreement with their theory. Particles with electric dipoles should behave similarly. A net dipole of an agglomerate greatly increases the influx of diffusion-limited material, as it provides a net long-range attractive force (due to spontaneous alignment) to other approaching dipoles.

The agglomeration enhancement due to amorphous water ice should occur not just for smaller agglomerates, as largely used to illustrate the arguments in this paper, but also for larger agglomerates, centimeters or more in size. In the latter case, the overall inelasticity should make fragmentation less likely, as would the increased cohesion. A collision potentially capable of disrupting the larger agglomerates would be particularly well suited at enhancing intergrain cohesion through collision-induced dipoles, via the mechanisms discussed in this paper. Collisions would also act to compact the developing planetesimal and decrease the likelihood of collisional obliteration.

The inner regions of a nebula are too warm for these water ice mechanisms to be directly important. However, even there dipolar forces may be of dominating importance. Of course, over the life of a solar system, inner planets will append quite a lot of material from outer nebular planetesimals (i.e., comets) that may have formed with aid from polar water ice. We suspect that the higher temperature materials in the inner nebula may also have very high dipoles as a result of vapor deposition–induced polarization, surface charge exchange, and pyro- and piezoelectric effects. Silica, silicates, and many other minerals are good prospects for these effects at the higher temperatures of terrestrial planet-star distances. Iron- and nickel-containing dust grains can also have magnetic dipoles and thus cannot (in the absence of magnetic monopoles) be as readily shielded as electric dipoles.

Therefore, in both the inner and outer regions of the nebulae, there are good physical reasons to believe that strong, persistent dipoles exist of a sufficient magnitude to promote rapid agglomeration, and the inelasticity of amorphous ice (in the outer nebulae) will greatly enhance sticking and suppress fragmentation.

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