THE STICKINESS OF CO_2 AND H_2O ICE PARTICLES: EFFECTS OF “VISCOELASTIC” ENERGY DISSIPATION ON THE THRESHOLD VELOCITY FOR STICKING. S. Arakawa[1] and S. Krijt[2], [1]Division of Science, National Astronomical Observatory of Japan (e-mail: sota.arakawa@nao.ac.jp), [2]College of Engineering, Mathematics and Physics Sciences, University of Exeter (e-mail: s.krijt@exeter.ac.uk).

Introduction: Pairwise collisional growth of dust aggregates is the first step of planet formation. The stickiness and collisional behavior of dust particles and aggregates have been studied [e.g., 1−3]. It is known that particles/aggregates composed of H_2O ice are generally stickier than rocky particles/aggregates [e.g., 4]. This difference plays an important role in models of dust evolution and planetesimal formation in the inner a few au of circumstellar disks [e.g., 5].

In the cold outer region of circumstellar disks, not only H_2O ice but also CO and/or CO_2 ices are important constituents of icy dust particles [e.g., 6]. Therefore, the stickiness of CO_2 ice particles may be of great importance for understanding the dust growth and radial drift behavior in circumstellar disks.

Laboratory experiments [7,8] revealed that CO_2 ice particles are less sticky compared to H_2O ice particles. It is proposed that this difference in stickiness would originate from the difference in the dipole moment [e.g., 9]. In other words, they claimed that the low threshold velocity for sticking of CO_2 ice particles might be due to the small surface free energy of non-polar CO_2 ice. However, we note that the literature value of the surface free energy of CO_2 ice (80 mJ m^{-2}, [10]) is comparable to that of H_2O ice (100 mJ m^{-2}, [11]). In addition, the values of elastic properties (i.e., the Young's modulus and Poisson ratio) are also similar between two materials. In the framework of the classical theory for dust growth [2,3], one would then expect the threshold velocity for sticking to be similar for H_2O and CO_2 ices.

In this study, we investigate another possibility to explain the low threshold velocity for sticking of CO_2 ice particles compared to that of H_2O ice particles. Krijt et al. [12] constructed a viscoelastic contact model. This model is the advanced version of the contact theory for perfectly elastic adhesive spheres, which is called JKR theory [13]. The viscoelastic contact model takes into account a crack propagation at the edge of the contact and an energy dissipation arising from “viscoelastic” behavior beneath the contact. Applying this model to H_2O ice particles, Gundlach and Blum [4] found that the threshold velocity for sticking is up to an order of magnitude higher than that predicted from JKR theory. Therefore, we can potentially explain the large difference in stickiness between H_2O and CO_2 ice particles reported by Musiolik et al. [7,8] if CO_2 ice particles follow more closely JKR theory for perfectly elastic adhesive spheres.

Typical Results for Collisions: Here we show the typical results for collisions between two equal-sized spheres of CO_2 ice. We set R_1 = 60 μm and $T_{\mathrm{vis}} = 10^{-9}$ s, and exploring a range of impact collision velocities V_{in}. Here R_1 is the particle radius and T_{vis} is the “viscoelastic” relaxation time which controls the strength of energy dissipation [4,12]. We found that there are three types of collision outcomes, namely, sticking collisions, bouncing collisions, and double collisions.

Sticking collision. The grey lines of Figure 1 show the time evolution of the contact radius, a, and the mutual approach, δ, for a head-on collision at V_{in} = 3.5 cm s^{-1}. The most important difference between our viscoelastic contact model and JKR theory is whether the kinetic energy dissipates during contact or not. For the case of V_{in} = 3.5 cm s^{-1}, the spheres cannot separate and instead oscillate back and forth. Both a and δ finally reach the stable state in JKR theory due to the dissipative effects when we use the viscoelastic contact model. In the framework of JKR theory, in contrast, the oscillation would not be dampened. The dissipative effects increase the threshold velocity for sticking.

Bouncing collision. Even if the dissipative effects work, collisions of two spheres will result in bouncing as the collision velocity is increased. The red lines of Figure 1 show the time evolution of a and δ for a head-on collision at V_{in} = 4.5 cm s^{-1}. In this case, the contact radius finally becomes $a = 0$, and the mutual approach and the approaching velocity are $\delta > 0$ and $\mathrm{d}\delta/\mathrm{d}t < 0$ at the end of the contact. At that point, the spheres separate and move away from each other.

Double collision. There exists a narrow range of impact velocities for which we can observe a “double collision”. This double collision occurs as a result of energy dissipations and viscoelastic cracking. The blue lines of Figure 1 show the evolution of a and δ for a head-on collision at V_{in} = 4.05 cm s^{-1}. In this case, the mutual approach and approaching velocity are $\delta > 0$ and $\mathrm{d}\delta/\mathrm{d}t > 0$ at the end of the contact. As $\mathrm{d}\delta/\mathrm{d}t$ is positive, two spheres are expected to re-collide after their separation. We therefore named this outcome as the “double collision”. We note that the collision velocity of the second collision is much lower than that of the first collision because of dissipative effects, and the second collision should result in sticking.

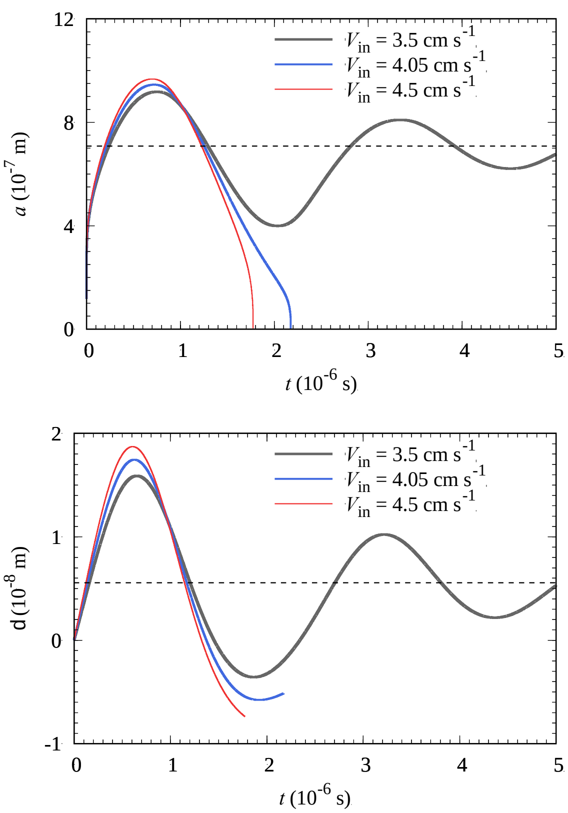

Figure 1. Time evolution of the contact radius, a, and the mutual approach, δ, for head-on collisions. The dashed lines represent the stable state in JKR theory [13].

Threshold Velocity for Sticking: We calculate the threshold velocity for sticking (i.e., the transition velocity from double collision to bouncing collision) using the viscoelastic contact model, and we also compare our numerical results with experimental data reported by Musiolik et al. [7,8].

CO_2 ice particles. Musiolik et al. [7] performed laboratory experiments of collisions of CO_2 ice particles within a vacuum chamber at a temperature of 80 K. The typical radius of the particles is R_1 = 60 μm. They found that the threshold velocity for sticking is V_{stick} = (0.04 ± 0.02) m s^{-1}. Figure 2 shows the dependence of V_{stick} on T_{vis}. As shown in Figure 2, V_{stick} hardly changes when $T_{vis} < 10^{-11}$ s. In this case, V_{stick} is almost identical to that of JKR theory. In contrast, when $T_{vis} > 10^{-9}$ s, the threshold velocity for sticking is several times higher than that predicted from JKR theory. We got the suitable range of T_{vis} to reproduce V_{stick} reported by Musiolik et al. [7] as follows: 8.5×10^{-11} s $< T_{vis} < 1.97 \times 10^{-9}$ s.

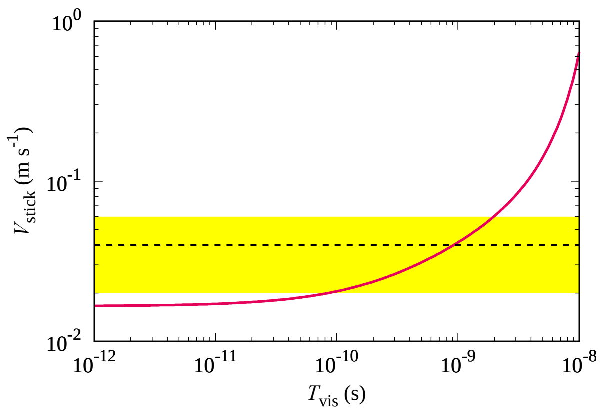

Figure 2. Dependence of the threshold velocity for sticking, V_{stick}, on the viscoelastic relaxation time, T_{vis}. The black dashed line represents the threshold velocity for sticking obtained from laboratory experiments and the yellow shaded region shows the uncertainty: V_{stick} = (0.04 ± 0.02) m s^{-1} [7]. The typical radius of CO_2 ice particles is R_1 = 60 μm.

H_2O ice particles. Musiolik et al. [8] also performed laboratory experiments of collisions of H_2O ice particles within a vacuum chamber at a temperature of 80 K. The typical radius of the particles is R_1 = 90 μm, and their experimental results suggest that V_{stick} ~ 0.73 m s^{-1}. We found that we cannot explain the reported value of V_{stick} by using JKR theory [13]. Assuming that the range of the surface free energy is 100 mJ m^{-2}, the required value of T_{vis} is approximately 9.8×10^{-9} s, and T_{vis} of H_2O ice particles with R_1 = 90 μm is an order of magnitude larger than that of CO_2 ice particles with R_1 = 60 μm.

Conclusion: Therefore, we concluded that the large difference in V_{stick} between CO_2 and H_2O ice particles would originate from the large difference in T_{vis}, i.e., the strength of viscoelastic dissipation.

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