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Self-propelling uneven Leidenfrost solids

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Placed on a hot surface, a solid that sublimates at atmospheric pressure can levitate on a cushion of its own vapor. Discovered by Leidenfrost, this effect has mostly been studied with liquids. Whereas the shape of a droplet is determined by a competition between gravity, surface tension, and stress in the vapor layer, a solid does not deform. In this paper, we show experimentally and theoretically that asymmetric mass distributions in a Leidenfrost solid can lead to a non homogenous vapor layer in which the lubrication flow generates a lateral force able to propel the body.

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Droplets, on a surface whose temperature is high above the boiling point of the liquid, levitate. In the Leidenfrost effect,¹ the strong evaporation creates a cushion of vapor whose pressure can be high enough to sustain the drop. The absence of contact with the substrate reduces a lot of the friction,² which generates bouncing³ and vibrations⁴ making the control of such drops problematic.⁵ Levitation and vapor production were exploited by Linke *et al.* who designed a substrate made of millimetric asymmetric teeth: a Leidenfrost drop placed on this ratchet gets propelled in a well-defined direction.⁶ The explanation for this effect has been recently debated.^{7–10} Linke suggested a viscous entrainment as responsible for the motion, which was confirmed by experiments and simulations where platelets of solid carbon dioxide were found to similarly self-propel on hot ratchets^{7,9,10} (Figure 1). Solid carbon dioxide, also called dry ice, sublimates at $-78\text{ }^{\circ}\text{C}$: left on a hot plate, it floats in the Leidenfrost state. Since dry ice is not deformable, the geometry is made much simpler compared to a liquid, which helped to confirm that propulsion arises from a viscous drive by the underlying vapor flow.^{9,10}

Unlike liquids, solids can be sculpted into different shapes. In this paper, we investigate experimentally and theoretically the behavior of uneven pieces of dry ice placed on horizontal smooth plates. To control the unevenness, we add a small weight on the side of a cylindrical platelet (Figure 2). The non-homogenous distribution of mass leads to non-uniform vapor layers, as sketched in Figure 3. The bottom of the dry ice is tilted by a small angle θ , the vapor layer being thinner where the body is heavier. As a consequence, the platelet does not remain at rest, it self-propels in

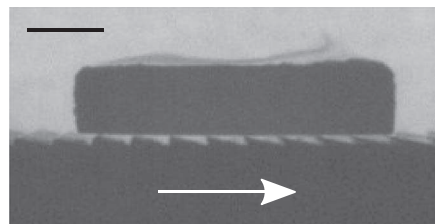


FIG. 1. A platelet of dry ice self-propels on a hot ratchet ($450\text{ }^{\circ}\text{C}$). The white arrow shows the direction of propulsion. The bar indicates 3 mm (enhanced online). [[URL: http://dx.doi.org/10.1063/1.4807007.1](http://dx.doi.org/10.1063/1.4807007.1)]

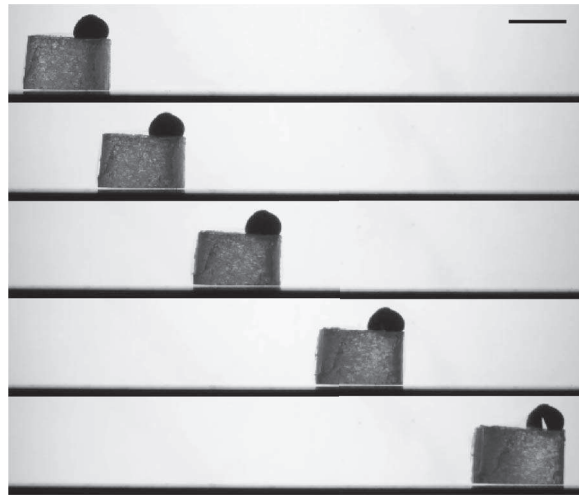


FIG. 2. A centimeter-size platelet of dry ice on a hot flat surface ($320\text{ }^{\circ}\text{C}$) with a small weight ($m = 0.54\text{ g}$) on the right side. The added mass tilts the platelet (by an angle $\theta = 0.3^{\circ}$), so that the ice gets propelled (enhanced online). [URL: <http://dx.doi.org/10.1063/1.4807007.2>]. Two pictures are separated by 0.3 s and the scale represents 1 cm. The asymmetry can also be made by sculpting the dry ice (enhanced online). [URL: <http://dx.doi.org/10.1063/1.4807007.3>]

the direction of the added weight. Geometrically, this system seems close to the one of axisymmetric platelets on ratchets:^{6–10} in both cases, the gap between the levitating solid and the substrate makes an angle (asymmetric platelet) or a series of angles (ratchet), which creates propulsion. However, the motion is directed toward the direction of closing angle for the asymmetric ice (Figure 2), whereas it takes place in the direction of opening angles over a ratchet (Figure 1).

The vapor flow exerts two forces on the platelet (Figure 3(b)): a viscous force F_S , parallel to the bottom surface, and a pressure force F_P , perpendicular to this surface. We expect F_S to be in the direction of opening angle, like for the ratchet where it is indeed the driving force. However, the bottom surface of the asymmetric platelet being tilted, the pressure force F_P also has a horizontal component θF_P that acts in the direction of propulsion. If it exceeds the viscous contribution ($\theta F_P > F_S$), the propulsion can indeed take place in the direction of closing angle θ .

Experiments are performed with dry ice platelets of radius $R = 7.6 \pm 0.4\text{ mm}$ and height $H = 10.0 \pm 0.5\text{ mm}$ hovering over a flat aluminum surface brought to a temperature of $320\text{ }^{\circ}\text{C}$. We record the ice trajectory $x(t)$ with a high speed video camera on a distance of 15 cm. Figure 4 shows the time-dependence of the velocity $v = x'(t)$ for three platelets with different added masses m of 0.21 g, 0.78 g, and 1.24 g. In comparison, the mass of the platelet is $M = 2.8\text{ g}$. The velocity of a platelet is a linear function of time, from which we can derive a constant acceleration x'' , and thus

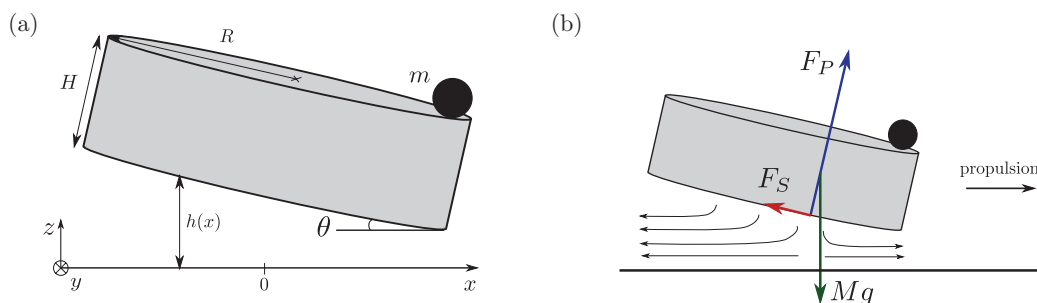


FIG. 3. (a) Sketch of the experiment: a platelet of dry ice of mass M with an extra weight of mass m on a side hovers above a flat surface. (b) Viscous force F_S and pressure force F_P applied by the vapor flow on the platelet.

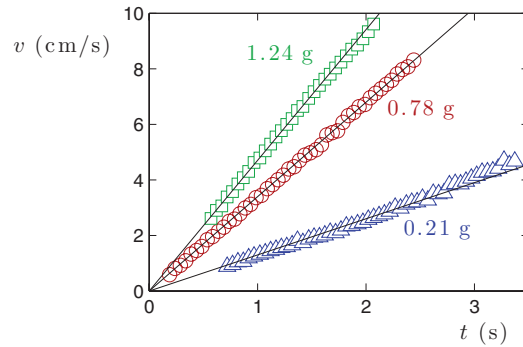


FIG. 4. Velocity v as a function of time for a given platelet (of mass $M = 2.8$ g) and different added weights (of respective masses $m = 0.21$ g, 0.78 g, and 1.24 g). The stronger the added mass, the more accelerated the platelet (enhanced online). [URL: <http://dx.doi.org/10.1063/1.4807007.4>]

deduce the propelling force $F = (M + m)x''$. We find forces on the order of $100 \mu\text{N}$, which increase with the added weight.

In order to understand the origin of the propelling force, we focus on the flow in the vapor layer (Figure 3). Due to the added weight, the platelet makes an angle θ with the horizontal. Experimentally, θ is typically 0.01 rad and it increases with m , always satisfying $\theta \ll 1$. Since the vapor layer is thin, with a thickness h_0 much smaller than R ($h_0 \approx 100 \mu\text{m}$ and $R = 7.6$ mm), the flow below a Leidenfrost solid can be described by a viscous flow in the lubrication approximation.⁹ The local flux conservation is written $\nabla \cdot (h\mathbf{U}) = V$, where $\mathbf{U}(x, y)$ is the horizontal velocity averaged along the z -axis, $h(x)$ is the local thickness of the vapor layer ($h = h_0 - \theta x$), and $V(x)$ is the velocity of the vapor ejected by sublimation at the surface of the platelet. Conduction dominates the heat transfer,¹¹ so that V is equal to $(\kappa/\rho L)(\partial T/\partial z)$, where T , ρ , and κ are, respectively, the temperature, the density, and the thermal conductivity of the vapor ($\rho = 1 \text{ kg/m}^3$, $\kappa \approx 0.03 \text{ W/m/K}$), and L is the latent heat of sublimation of dry ice ($L \approx 7.10^5 \text{ J/kg}$). Since $R \gg h$, we assume $\partial T/\partial z \approx \Delta T/h$, where ΔT is the temperature difference between the solid and the platelet ($\Delta T \approx 400^\circ\text{C}$). \mathbf{U} is calculated assuming a Poiseuille law in the vapor layer: $\mathbf{U} = -(h^2/12\eta)\nabla p$, where $p(x, y)$ is the vapor pressure and η its dynamic viscosity ($\eta \approx 2.10^{-5} \text{ Pa s}$). This particular case of Darcy's law is obtained for a flow in a narrow gap, averaged over the perpendicular coordinate (z -axis here). With the conservation of flux, it leads to the differential equation

$$\nabla \cdot (h^3 \nabla p) = -\frac{12\eta\kappa\Delta T}{\rho Lh} \quad (1)$$

with the condition $p = 0$ on the vapor layer boundary. $h(x)$ can be written $h_0(1 - \varepsilon x)$ with $\varepsilon = R\theta/h_0$. Assuming $\varepsilon \ll 1$, we expand p in ε , $p = p_0 + \varepsilon p_1 + \mathcal{O}(\varepsilon^2)$, and solve the two first orders in Eq. (1) (see the supplementary material for the whole calculation¹²). We calculate the pressure force F_P and the shear force F_S that are, respectively, normal and tangential to the bottom face of the platelet, as well as the moment of the pressure force around the y -axis, Γ_P . We obtain at first order:

$$F_S = -\int_S \eta \left(\frac{\partial u_x}{\partial z} \right)_h dS = -\frac{3\pi}{4} \frac{\eta\kappa\Delta T R^3}{\rho Lh_0^3} \varepsilon, \quad (2a)$$

$$F_P = \int_S p dS = \frac{3\pi}{2} \frac{\eta\kappa\Delta T R^4}{\rho Lh_0^4}, \quad (2b)$$

$$\Gamma_P = -\int_S x p dS = -\frac{11\pi}{16} \frac{\eta\kappa\Delta T R^5}{\rho Lh_0^4} \varepsilon, \quad (2c)$$

where S is the bottom surface of the platelet ($S = \{(x, y) | x^2 + y^2 \leq R^2\}$). The projection of F_S and F_P on the vertical axis balances the weight: $F_P \cos \theta - F_S \sin \theta = (M + m)g$. Since we have $\theta \ll 1$

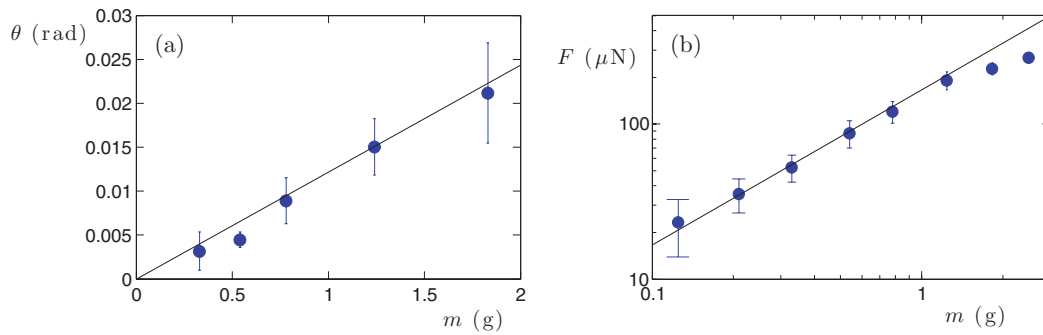


FIG. 5. (a) Measured angle θ as a function of the added mass m . The solid line represents Eq. (4), its slope is given by $24/(11M)\sqrt{b/R} = 12 \text{ rad/kg}$. Each point is an average on five measurements. (b) Measured driving force F as a function of the added mass m . The solid line corresponds to Eq. (5). Each point is an average on ten measurements.

and $F_S\theta/F_P \sim \theta^2$, this balance leads to $F_P = (M + m)g$, which yields the mean thickness of the vapor layer,

$$h_0 = \sqrt{bR}, \quad (3)$$

where the distance b is $[3\eta\kappa\Delta T/2\rho\rho_0LgH(1 + m/M)]^{1/2}$, with ρ_0 the dry ice density ($\rho_0 = 1560 \text{ kg/m}^3$) and H the platelet height. As expected, we find the expression of the film thickness for an axisymmetric system.⁷ Using Eq. (3) and assuming the additional mass to sit right at the edge of the cylinder, the moment balance around the y -axis, $\Gamma_P + mgR = 0$, leads to

$$\theta = \frac{24}{11} \frac{m}{M} \sqrt{\frac{b}{R}}. \quad (4)$$

A first consequence of Eq. (4) is to show that our hypothesis $\varepsilon \ll 1$ is equivalent to $m \ll M$ ($\varepsilon = R\theta/h_0 \sim m/M$), roughly obeyed in our experiments. Then the expression of b simplifies to $(3\eta\kappa\Delta T/2\rho\rho_0LgH)^{1/2}$, which only depends on physical constants and on the platelet height H , with a typical value of $1 \mu\text{m}$.

We finally project F_S and F_P on the horizontal axis to obtain the propelling force: $F = F_S + \theta F_P$. Equations (2a) and (2b) show that both components of F have the same scaling yet opposite directions. However, it is found that the contribution of the pressure θF_P is twice the contribution of the shear F_S (see the supplementary material for more details¹²). The propelling mechanism in this system is then different from the one in the ratchet, making ice move in the opposite direction towards the narrow side of the gap. On the whole, the propelling force can be written: $F = Mg\theta/2$. This very simple expression mixes the genuine driving force of the motion (the weight of the solid, which forces a vapor flow below) with its cause (the angle θ , which quantifies the degree of asymmetry of the system). Together with Eq. (4), we obtain

$$F = \frac{12}{11} mg \sqrt{\frac{b}{R}}. \quad (5)$$

These findings can be compared to experiments. First, Figure 5(a) shows the measured angle θ as a function of the added mass m . The platelets are the same as described previously. We take a picture of a moving platelet and we measure θ directly, after magnifying the pictures (each point is an average on five measurements). The solid line shows Eq. (4) calculated with the numerical values of the different parameters. The model is in good agreement with the experiments: the angle increases linearly with m and Eq. (4) nicely fits the data without any adjustable parameter. Second, Figure 5(b) shows the force (deduced from the acceleration of the platelet) as a function of the added mass. The solid line is plotted using Eq. (5). Again, we observe a linear increase (the solid line has a

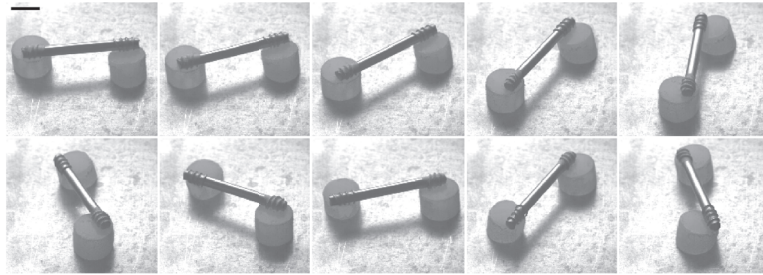


FIG. 6. Two platelets of dry ice linked by an off-centered steel rod rotate. Two successive pictures are separated by 200 ms and the bar shows 2 cm. The angular acceleration deduced from these pictures is $2.0 \pm 0.1 \text{ rad/s}^2$ (enhanced online). [URL: <http://dx.doi.org/10.1063/1.4807007.5>]

slope 1 in this log-log plot) quantitatively agreeing with the experiment. This agreement (established in the limit $m \ll M$) becomes logically less convincing as m exceeds 2 g, i.e., when it approaches M .

This model was developed for a static platelet. However, its velocity v generates other flows (around, below), which might influence the motion. First, the platelet undergoes friction. Its origin can be either the shear in the vapor layer $\eta(v/h_0)R^2$ or the inertial friction ρRHv^2 from the surrounding air of density ρ . Both forces balance the propelling force for a velocity of a few meters per second. In our experiments the velocity of the platelet never exceeds 10 cm/s (Figure 4), so that we can neglect the friction in our measurement of the propelling force. Second, a well-known feature of the lubrication theory is that a tilted surface hovering over a horizontal wall creates a Poiseuille-Couette flow and thus undergoes a pressure force.¹³ In our case, the direction of propulsion in relation with the orientation of θ creates a depression: the resulting force F_{Pv} is normal to the bottom surface of the platelet and opposed to F_P . In the limit $\varepsilon \ll 1$, F_{Pv} scales as $\eta v R^4 \theta / h_0^3$. For $v \approx 10 \text{ cm/s}$, F_{Pv} is on the order of 100 μN , that is, much smaller than F_P : $F_P \approx Mg \approx 30 \text{ mN}$. This effect does not alter the propulsion either.

In comparison with a platelet on a ratchet, the propelling force obtained here is almost one order of magnitude higher.⁹ Moreover, the absence of texture in the surface prevents the platelet to sink and to get stuck: this system is much more efficient to propel Leidenfrost solids. Yet, the orientation of the force differs between both systems. With the ratchet, it is set by the substrate with the geometry of the textures, whereas the asymmetric platelet carries this orientation, which makes it change if the platelet rotates.

To consider the case of rotation, we study a device built such that the two coupled platelets are forced to move in opposite directions. As shown in Figure 6, the system consists of two cylinders of dry ice (mass $M = 2.5 \text{ g}$) linked by an off-centered steel rod of length $l = 4.2 \text{ cm}$ and mass $2m = 4.4 \text{ g}$ that also acts as an added mass for the platelets. As seen in the figure, a rotation naturally results from this geometry. In addition, the motion accelerates as it does for the propulsion of single platelets. The angular acceleration in this example is 2.0 rad/s^2 . We expect an acceleration $2F(m)/(m + M)l$, where the force F is of order 200 μN for an added mass per platelet of 2.2 g, as seen in Figure 5(b). The resulting acceleration is thus 2.0 rad/s^2 , as observed experimentally.

The propulsion can also be seen with other solids, like camphor, as presented in Figure 7. Camphor's melting point is 179°C , and its boiling point is 204°C . Both temperatures are close, so that a piece of solid camphor put on a hot plate is surrounded by a small quantity of liquid camphor and the whole object levitates. Solid and liquid Leidenfrost effects here combine and the resulting object propels if a small mass is added on one side.

We showed that uneven platelets of dry ice can self-propel on a hot surface, and rotate when coupled together. The propulsion is due to the pressure exerted by the vapor flow on the bottom of the platelet. This surface is not parallel to the substrate but gets tilted by an angle θ . The pressure generates a lateral force $Mg\theta/2$ creating a “continuous ratchet.” This questions the evolution of the shape of the platelet while it sublimates. Since the thinner the vapor layer, the stronger the sublimation, the loss of matter is asymmetric below the platelet. Thus, the propelling force should be altered, which might be observed by following such objects on large distances. It would be also

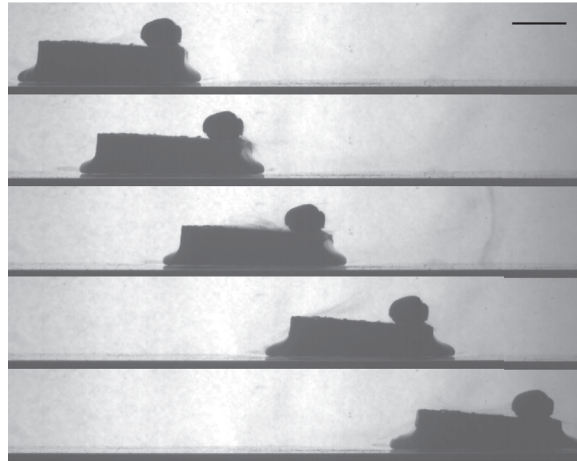


FIG. 7. A square platelet of camphor (6.0 g) with a small mass of 1.8 g on a hot plate (400 °C). Although the solid is now surrounded by liquid camphor, the whole object still self-propels. Two pictures are separated by 0.65 s and the scale represents 1 cm (enhanced online). [URL: <http://dx.doi.org/10.1063/1.4807007.6>]

worth seeing how the propulsion is modified by the vapor flux: for instance, non-evaporative solids and liquids can be levitated by air flowing from the substrate with a velocity that does not depend on the thickness of the air layer.¹⁴ Finally, our results can be generalized to any Leidenfrost solid whose center of mass is not vertically aligned with the center of pressure on the bottom surface.

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