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Feasibility of large free-standing liquid films in space

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We consider the feasibility of large-scale free-standing thin liquid film experiment in the space environment as a new realization to study two-dimensional hydrodynamics. We identify material and environmental criteria necessary to avoid freezing, evaporation, chemical degradation, and spontaneous collapse of the film. These criteria pose no obstacles to achieving films of kilometer scale and lifetime of many months, with attainable Reynolds number up to 10^7. However, impacts from meteoroids pose a serious threat to the film, and require substantial shielding or unproven self-healing properties in the film. Current theoretical and experimental studies of two-dimensional turbulence are briefly reviewed. We also describe a specific candidate liquid for the film.

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I. INTRODUCTION

Macroscopic thin liquid films are prevalent in nature and technology. To understand their physical properties is theoretically important and experimentally instructive [1–4]. Thin liquid films are useful tools for industrial applications and scientific explorations [5]. In particular they are conventional experimental realizations to study two-dimensional hydrodynamics and turbulence [6].

Two-dimensional hydrodynamics plays a special role in space science [7]. Two-dimensional flows with high Reynolds numbers may organize spontaneously into large-scale coherent patterns [8,9] that are common features of geophysical and astrophysical flows. Some phenomena, such as surface-tension-driven flows and thermocapillary flows, have important applications in space-related techniques [10].

The space environment, on the other hand, provides some unique conditions for experimental physics. In particular, the micro gravity and vacuum in space are ideal environments for large-scale experiments that are not feasible in the normal laboratory environment.

In this paper we propose a realization of a large-scale free-standing liquid film in the space environment to study two-dimensional hydrodynamics. Compared to conventional experimental realizations, the film-in-space experiment is appealing for the following reasons. First, among the factors causing the rupture of macroscopic thin films under normal laboratory conditions, the primary factor is drainage due to gravity. We expect the microgravity environment will extend the film lifetime against the drainage-induced rupture. Second, the space environment makes it possible to study large-scale flows in the film. In particular the environment permits flows of higher Reynolds number and hence an improved study of two-dimensional turbulence. Last, in current experiments based on conventional soap films [11] and other realizations [6], the underlying dynamics inevitably couples with the adjacent matter such as gaseous and solid boundary layers. These couplings create technical difficulties and cloud interpretation of the experiments. The space films can readily help overcome these obstacles and improve our understanding of two-dimensional hydrodynamics, with its distinctive form of nonlinearity and turbulence.

This paper assesses the potential for creating, maintaining, and manipulating large-scale free-standing liquid films in the space environment. We shall base our study on conventional stability theory of soap films [12]. The design of the space film requires an unusual combination of fluid properties, such as extremely low vapor pressure and appropriate viscosity and surface tension, in order to maintain the film in a stable liquid state. After initial assessment of these properties, we consider explicitly the commercial liquid Dow Corning 705 (DC 705) diffusion pump oil [13] as a possible candidate film liquid. DC 705 oil (penta-phenyl-tri-methyl-tri-siloxane) is a colorless to straw-colored, single component fluid designed for ultrahigh vacuum applications. Conventional pump oils such as this give extremely low evaporation rates with minimal increase in viscosity. We include its detailed physical and chemical properties in the Appendix.

For definiteness, we assume the space film to be a circular film with diameter $L=1$ km and thickness $h=1$ μm, maintained at a temperature $T_0=298$ K over a lifetime of a year. Accordingly the total mass of the base liquid is of the order of 10^3 kg. Based on these assumed parameters and the candidate liquid properties, we can study the feasibility of the film under different external influences expected from the space environment and suggest potential difficulties and possible solutions. Moreover using these parameters as a base case and known scaling laws, one may readily estimate effects of changing these parameters.

We also consider as an alternative the "black film" [14], which is a stable film configuration with thickness of the order of a few hundred angstroms. The black film therefore deviates from the standard stable thin-liquid-film model and our assumed physical conditions, and requires alternative feasibility studies that yield different estimates. We shall briefly discuss the advantages and shortcomings of the black film.

In the next section we prescribe the thermodynamic properties required to maintain the thin film in a liquid state with little evaporation. In Sec. III we consider the stability of the film against spontaneous rupture and discuss the requisite

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properties of the compatible surfactants that ensure the stability. We then analyze the possible damages to the film from external influences in the space environment in Sec. IV. In Sec. V we review the background for two-dimensional hydrodynamics and turbulence, and estimate parameters such as the Reynolds number achievable for the film. We also compare the space film with current experimental realizations in Sec. VI. For completeness, we consider in Secs. VII and VIII various forces, both external and internal, and time scales relevant for the film design. In the Discussion section we suggest some alternatives to the standard film model and possible generalizations to other experiments in the space environment. We present our conclusion in the final section.

II. REQUISITE THERMODYNAMIC PROPERTIES TO MAINTAIN THE LIQUID STATE IN SPACE

A. Temperature

To keep the film from freezing, the radiative cooling must be compensated by an influx of solar energy. The solar radiation flux at the earth orbit is $J=1.37\times 10^3$ W/m^2 [15]. Thus using the blackbody approximation and applying the Stefan-Boltzmann law $J=\sigma_0 T^4$, we find the equilibrium film temperature $T=394$ K.

The film must be transparent in order to be warmed uniformly. Perfect absorption cannot be realized in transparent media, however. The equilibrium temperature thus must be lower than 394 K. If this temperature is too low to maintain the fluidity, we can readily raise it by dispersing absorbing particles such as carbon black in the transparent liquid. By adjusting the volume percentage of these absorbing particles, the film temperature can be kept in a range up to the blackbody temperature T. Our assumed baseline temperature $T_0=298$ K is thus feasible.

Constancy of solar flux is important. If the sunlight is interrupted, the film cools rapidly. There are two time scales associated with the cooling process. One is the thermal equilibration time t_1. It is the time for the film to reach thermal equilibrium via conduction. The other time scale t_2 is the time to freeze via radiative cooling.

The time t_1 is approximately given by h^2/ζ, where h is the film thickness and ζ is the thermal diffusivity. It is of the order of 10^{-6} m^2/s for typical liquids [16]. We thus find

$$t_1 \sim 10^{-6}\ \mathrm{s}. \tag{1}$$

To estimate t_2, we use the blackbody emission approximation [17,75]. The balance of heat flux demands

$$cAh\,dT = -2AJ\,dt, \tag{2}$$

where J is the radiative flux $\sigma_0 T^4$ as dictated by the Stefan-Boltzmann law. c is the specific heat and is of the order of 10^7 J/K m^3 for normal liquids [16]. A is the surface area, and h is the film thickness. If the film temperature decreases from T_2 to T_1, we find via integration

$$t_2 = \frac{ch}{6\sigma_0}\left(\frac{1}{T_1^3} - \frac{1}{T_2^3}\right). \tag{3}$$

Our candidate liquid freezes at about 200 K [13]. We thus take $T_1=200$ K and $T_2=300$ K, and it follows from Eq. (3) that

$$t_2 \lesssim 1\ \mathrm{s}. \tag{4}$$

The system thus rapidly reaches equilibrium via conduction [Eq. (1)] and freezes within a few seconds [Eq. (4)] if the incoming solar radiation flux is blocked. A frozen part could make the film shatter and should be avoided. Thus the orbit of the system should be designed in such a way that the film is kept constantly in the sunlight.

B. Vapor pressure

The lifetime τ of a liquid film against evaporation is determined by the film thickness h, the evaporation mass flux ϕ (mass per unit area per unit time), and the liquid mass density ρ through the relation

$$\tau = \frac{\rho h}{\phi}. \tag{5}$$

For a micron-thick film with $\rho=10^3$ kg/m^3, a lifetime of at least 1 year thus requires

$$\phi \leqslant 10^{-10}\ \mathrm{kg/m^2\,s}. \tag{6}$$

Thus a film of a conventional liquid with the designed geometry would evaporate in seconds in the space environment. Proper liquids need to be chosen to achieve such a small evaporation flux.

The evaporation flux ϕ of a liquid is related to its vapor pressure p through the Langmuir formula [18]:

$$\phi = p\sqrt{\frac{m}{2\pi RT}}, \tag{7}$$

where m is the molar molecular weight and $R=8.31$ J/mol K.

Dow Corning 705 diffusion pump oil has typical product properties $m=0.546$ kg/mol and $p=3\times 10^{-10}$ torr at 298 K as introduced in the Appendix. Using these values, we infer via Eq. (7) that at the baseline temperature 298 K the evaporation flux is 2×10^{-10} kg/m^2 s, which is larger than the condition Eq. (6). Further manipulations are therefore needed in order to reduce the vapor pressure and hence the evaporation flux.

Vapor pressure can be reduced by lowering temperature. Using the vapor pressure-temperature relation Eq. (A1) for DC 705 fluid, we find that the condition Eq. (6) is satisfied at about 273 K. However, this reduced temperature increases film viscosity, which is an unwelcome property. We discuss this issue in the Appendix.

Alternatively we can also achieve smaller evaporation flux with larger molecular weight in the same class of molecules. The dependence of flux ϕ on molecular weight follows from the Eyring kinetics [19],

$$\phi \approx \frac{\rho_s}{t_a} \exp\left(-\frac{U}{k_b T}\right), \tag{8}$$

where ρ_s is the surface density of molecules, $1/t_a$ is the attempt rate, and U is the binding energy of a molecule to the liquid, which is proportional to molecular weight. For polymers with N repeat units, U is roughly proportional to N and thus

$$\phi \approx \frac{\rho_s}{t_a} \exp(-\alpha N), \tag{9}$$

where α is a numerical factor and depends on temperature. Our candidate liquid is such a polymer with $N=3$.

In the same class of molecules as our candidate liquid, we now estimate the proper N value that yields the requisite flux ϕ [Eq. (6)] at $T_0=298$ K, assuming ρ_s/t_a weakly depends on molecular weight. Combining Eqs. (7) and (8), we have

$$p = \frac{\rho_s}{t_a}\sqrt{\frac{2\pi RT}{m}} \exp\left(-\frac{U}{k_b T}\right). \tag{10}$$

Using available data for DC 705 fluid [13] and Eqs. (9) and (10), we find at $T_0=298$ K the requisite evaporation flux Eq. (6) can be satisfied for

$$N \geqslant 4. \tag{11}$$

Equation (11), in connection with Eqs. (6) and (7), leads to

$$p < 10^{-11} \text{ torr}. \tag{12}$$

With modest increment in molecular weight, one can thus achieve significantly smaller evaporation flux and realize the designed lifetime of a year against evaporation in the space environment.

III. STABILITY OF THE THIN LIQUID FILM AGAINST SPONTANEOUS RUPTURE

Thermal fluctuations in thin liquid films eventually cause them to collapse. This important process has been studied in detail [12,20–23], and the predicted lifetime against spontaneous rupture has been experimentally confirmed [24,25].

In the following we use the analysis of Sharma and Ruckenstein [12,26] developed for soap films to estimate the lifetime of the space film against spontaneous rupture. This work treats both single component films and films whose surfaces are saturated with insoluble surfactants. The stability of the film depends on thickness h, dynamic viscosity η of the film liquid, surface tension σ, and surface concentration Γ (number of surfactant molecules per unit area) of surfactants. Although surface tension helps to stabilize the film, the long range force, i.e., the van der Waals disjoining pressure, tends to destabilize and eventually rupture it. When h is small, typically a few micrometers, one can employ finite-amplitude perturbative analysis to find the time constant τ of the fastest growing wave vector k_m of sinusoidal film surface modulations [12].

In the case of free thin films devoid of surfactants, one finds that the fastest growing wave vector goes to zero, and

$$\frac{1}{\tau} = \omega_0 = \frac{A}{4\pi\eta h^3}, \tag{13}$$

where A is the Hamaker constant which characterizes the van der Waals potential. It is of the order of 10^{-20} J for silicone oils like our candidate liquid.

In the case of free thin films with excess insoluble surfactants, one finds

$$k_m = \frac{1}{h}\sqrt{\frac{A}{2\pi\sigma h^2}} \tag{14}$$

and

$$\frac{1}{\tau} = \omega_1 = \frac{A^2}{96\pi^2 \eta\sigma h^5} = \frac{(k_m h)^2}{12}\omega_0. \tag{15}$$

Using the tabulated data for DC 705 oil, for the surfactant-free case we find

$$\tau \sim 10^2 \text{ s}, \tag{16}$$

and for the case with excess surfactants,

$$\tau \sim 10^9 \text{ s} \approx 100 \text{ years}, \tag{17}$$

$$k_m \sim 10^2 \text{ m}^{-1}. \tag{18}$$

The estimate Eq. (16) makes the surfactant-free film infeasible whereas the case with excess surfactants [Eq. (17)] yields more-than-adequate lifetime. Compatible surfactants are therefore necessary for the space film to achieve the designed lifetime against spontaneous rupture.

Experiments [27] have confirmed that excess surfactant concentration decreases the dominant perturbation wavelength and frequency, and thus stabilizes thin liquid films. Rupture requires thinning of the initial film to molecular dimensions. This thinning requires outward flow of the film away from the thinnest region. Without surfactants, the fluid velocity is nearly uniform throughout the thickness of the film. But an insoluble surfactant layer inhibits flow at the surface, due to the viscoelastic effect of the surfactant, so that the outward fluid velocity must nearly vanish at the surface. Instead of being uniform throughout the thickness, the velocity profile is therefore a parabolic Poiseuille flow. Thus a given flux of fluid and a given thinning rate would require a much greater shear rate and much greater dissipation when the surfactants are present. Since the rate of dissipation is limited by the gain in van der Waals energy, the surfactant-coated film thins more slowly than the uncoated film. Moreover since aggregation of surface-active agents modifies the local surface tension, surfactants can reduce the thinning flow by creating an opposing gradient in surface tension as explained by the conventional Gibbs-Marangoni theory [28].

The above analysis assumes that the surfactants are insoluble and surfactant molecules are tightly packed to form a monolayer at each surface with the liquid film in between. If surfactants are not completely insoluble, there will be diffusion of surfactants in the bulk of the film and exchange of surfactants between the bulk and the surfaces. These processes may reduce the film stability. Theoretical and numerical studies [1,29] show a weak dependence of the rupture time on solubility of surfactants but a strong dependence on the surface viscosity η_s that characterizes the viscoelastic stress in surfactant monolayers. In addition, the rupture time also depends strongly on the Marangoni parameter which characterizes how effectively the surfactant concentration can modify surface tension.

The existence of appropriate surfactants for the unconventional liquid of our film should not be taken for granted. The pump oils that provide needed properties of liquidity and nonvolatility also have low surface tension. This low initial surface tension limits the scope of compatible surfactants. In order to be effective, surfactants must segregate to the surface, and this must lower its surface tension significantly. However, it may not be easy to find surfactants that can reduce the surface tension below that of the pump oil we have chosen. In addition, the surfactant monolayers need to be strong enough to yield large viscoelastic effect to ensure the film stability. Some possible candidate surfactants for the pump oil are those used in oil foaming [30], where surfactants are crucial to stabilize the microscopic plateau films between adjacent oil bubbles.

The stability model we have referred to essentially assumes infinite lateral scale, while in actual implementation the space film must be laterally finite and supported by a frame. For a conventional wetting frame, the negative Laplace pressure difference at the solid-liquid interface may drain the liquid toward the frame. The resulting thinning region immediately near to the frame may break and hence limit the film lifetime. Therefore the frame must be engineered by choosing surface wetting properties and by adjusting local interface geometry [31] to counter the draining effect. For example, a possible optimal frame can have a wedgelike boundary with an extending thin edge towards the film. The sides of the edge can be rendered nonwetting while the tip of the edge allows maximal wetting. A frame like this can achieve a positive film surface curvature at the boundary and hence a positive Laplace pressure difference. Thus the draining effect due to the frame can be overcome though further experimental tests are needed. On the other hand, the possible thinning near the frame boundary suggests the "black film" configuration, and we shall revisit it in the Discussion section.

The case of excess insoluble surfactants yields more-than-adequate lifetime, and this leaves room for us to further adjust film viscosity and thickness for experimental purposes. For instance, by lowering viscosity we can improve fluidity and thus enhance the dynamics in the film. Optimal viscosity and film thickness should be decided in connection with other properties of the space film that we shall consider later.

IV. EXTERNAL IMPACTS IN THE SPACE ENVIRONMENT

There are both potential chemical and physical impacts and damages to the film in the space environment.

The potential chemical damage comes from radiation; this can degrade the film in two different ways [32]. Radiation can ionize oxygen and double-bonded atoms in the environment. The resultant ions and free radicals can interact with film molecules and damage the film. In space this damage can be effectively reduced by avoiding low-earth orbit and therefore drastically reducing these ions and free radicals. Radiation can also ionize film molecules directly and degrade the film. Materials with sufficient resistance to radiation are therefore required in order to reduce this aspect of damage. Because of its high phenyl content, DC 705 pump oil has ideal resistance to radiation among all organic compounds [33,76], and it is stable in the radiative space environment [13]. Radiation damage thus poses no problem for the space film based on such a liquid.

Micrometeoroids, however, may damage the film via physical impacts. Incoming meteoroids affect the film both mechanically and thermally. These particles may punch holes in the film directly by knocking out columns of film liquid. They may also sail through or stay in the film, depositing in it most of their energy and exciting elastic waves. At the same time, part of the kinetic energy of these particles will be transferred to the film in the form of thermal energy. This process will increase local temperature and consequently change the local properties such as surface tension and viscosity. It can even evaporate film liquid in the impact regions and produce high pressure gas in the holes. We must assess these potential physical damages and propose possible ways to reduce them.

A. Meteoroid-induced hole nucleation in the film

Since both mechanical and thermal effects of meteoroid impacts generally produce holes in the film, we now first focus on a single hole and analyze how it forms, evolves, and affects the film.

If a hole in the film is too large, it will be unstable and will continue to expand [34]. We study the stability of a dewetting hole of radius r by considering the change of free energy $\Delta F(r)$ associated with the formation of the hole. We ignore long range forces and consider only surface energy. We assume the shape of the hole to be semicircular in cross section, and $r \ll L$. The change of free energy is

$$\Delta F(r) = \sigma(2\pi r h - 2\pi r^2) \tag{19}$$

and

$$\frac{d\Delta F}{dr} = 2\pi\sigma(h - 2r). \tag{20}$$

The condition $d\Delta F/dr=0$ demands $r=h/2$ which is the critical size of a dewetting hole. If the radius of the hole is smaller than $h/2$, $d\Delta F/dr>0$, and the hole will shrink and eventually disappear. Otherwise $d\Delta F/dr<0$, and the hole will expand and potentially damage the film.

It was found experimentally [35] that dewetting holes expand at a constant velocity [77]. The classical Dupre-Culick law [36] provides simple estimate of the expansion velocity V. The dewetting hole is surrounded by a rim collecting the liquid, where the dynamics localizes. The change of momentum per unit length of the rim satisfies

$$\frac{dP}{dt} = V\frac{dm}{dt} = 2\sigma, \tag{21}$$

where m is the mass of the rim per unit length. Since $dm/dt=\rho hV$ where ρ is liquid density, we can solve for V,

$$V = \sqrt{\frac{2\sigma}{\rho h}} \approx 1 \text{ m/s}. \tag{22}$$

The expanding hole can reach the boundary of the film within 1 hour.

Thus a hole with size of order h or greater will expand and eventually destroy the film and must be avoided. If an incoming meteoroid of size r can produce a hole of size h in the film, a necessary condition is that its kinetic energy $K=2/3\pi r^3\rho_m v^2$ must overcome the surface energy $2\pi\sigma h^2$, i.e.,

$$r > r_c = \left(\frac{3\sigma h^2}{\rho_m v^2}\right)^{1/3} \approx 10^{-9} \text{ m}, \tag{23}$$

where the meteoroid density ρ_m is about 5×10^3 kg/m^3, and the incoming speed v is as high as 30 km/s [78]. r_c thus sets a lower bound for the size of incoming meteoroids that are dangerous to the film.

Equation (23) also shows that for an incoming meteoroid with size comparable to h or greater, its kinetic energy is much larger than the corresponding surface energy of the impact area, and the surface tension can be ignored during the impact. Consequently a meteoroid of such a size will simply knock out the corresponding column of the film liquid and produce an expanding hole.

Thus incoming meteoroids with sizes larger than $h=10^{-6}$ m are dangerous to the film while meteoroids with size smaller than $r_c=10^{-9}$ m are harmless. More detailed studies of the interaction process are needed with respect to sizes $r_c<r<h$.

B. Interactions between meteoroids and the film

Meteoroids interact with the film both mechanically and thermally. They can directly impart momentum to the film during collisions, and the momentum propagates in the film via elastic waves or shock fronts [37]. They can also boil the local film liquid, and the resultant high-pressure gas transfers its energy to the film via rapid expansion. At the same time viscous dissipation reduces the kinetic energy to thermal energy. The total effect of the impact is therefore the result of the competing propagation process and dissipation process.

The detailed interaction thus depends on many physical properties and is a very complicated problem in engineering. First-principles estimation of this process goes beyond the scope of the paper. To estimate the impact effect, we instead consider available empirical information.

In the formation of craters due to high-speed meteorite impact on an astronomical body, an empirical relation between the diameter d of a crater and the total kinetic energy K of the incoming meteorite is given by [38]

$$d \propto K^{1/3}. \tag{24}$$

The proportionality coefficient is of the order of unity in SI units.

If we apply the relation Eq. (24) to the formation of holes in the space film and insert the expression for the kinetic energy $K=2/3\pi r^3\rho_m v^2$, we find

$$D \approx 10r, \tag{25}$$

where D is the diameter of the hole and r is the size of the meteoroid. Thus a meteoroid with size $0.1h=10^{-7}$ m can produce a hole of size h and should be avoided, while meteoroids with smaller sizes would not destroy it according to this criterion.

The hole size based on relation Eq. (24) could be overestimated. The cratering process gives only a rough guide to the expected hole size D. Craters form at the surface of a bulk material rather than a thin layer. Thus the confinement of energy and stress is likely greater in the cratering geometry. Moreover the solid material forming a crater is stronger than the liquid material of our film. Both these effects would be expected to increase the retarding forces on the projectile. Furthermore, in forming the crater, the incoming meteorite fragments and cannot pass deeply into the solid medium. Most of its initial energy is thus released near to the impact surface, and there is severe jetting. All these effects lead to greater disturbance in a smaller volume. It is thus natural that greater damage is done in the catering geometry so that the hole diameter would be expected to be larger there.

High-speed impact has also been studied using silica aerogel as the target. Aerogel is a highly porous solid material with a density of 50 kg/m^3 [39], and it has many exceptional physical and chemical properties. Both simulations based on fired projectiles and actual results from meteoroids trapped in aerogel suggest that high-speed meteoroids can penetrate the aerogel to a depth of an order of 10 to 100 times the size of the meteoroids, without severe heating or fragmentation [40]. The typical impacts produce carrot-shaped tracks that begin with entry holes one order of magnitude wider than the diameters of incoming meteoroids. There are no obvious fracturing near the tracks.

Different and independent experimental evidences thus lead to the same empirical relation Eq. (25). The solid medium where craters form is stronger than the liquid film while the aerogel, with density of 1/20 of that of DC 705 liquid, is much weaker. Interactions with high-speed projectiles can be qualitatively different in different media with different geometries. Our findings, however, suggest that the empirical relation between the hole size and the diameter of the incoming projectile is robust in a broad spectrum of impact medium properties. It is thus feasible to assume the same relation in the case of space film, i.e., the incoming meteoroid with size $0.1h$ will produce a hole of size h and should be avoided. Exact results with respect to meteoroid size should be determined by further experimental tests in the actual liquid environment.

C. Meteoroid flux and mass concentration

The flux of meteoroids (number of impacts per unit area per unit time) of mass m and greater satisfies the empirical power law [41]

$$n(m) = n_0\left(\frac{m}{m_0}\right)^{\alpha}, \tag{26}$$

where α is the mass distribution index, m_0 is a constant with dimension of mass, and n_0 is the flux of mass m_0 and greater.

The meteoroid flux is largest near the earth orbit, and further away from the earth the interplanetary particle flux is reduced [42]. Earlier measurements [43] showed that α ranges between -0.27 and -0.34 at mass threshold of 10^{-9} kg in the space region between 1 and 1.6 AU. At mass threshold of 10^{-12} kg, measurements by Pioneer 11 showed that α is -0.5 between 2 and 5 AU [44].

Moreover at mass threshold of 10^{-12} kg, the detectors on Pioneer 10 and 11 recorded an almost constant penetration flux of 10^{-6} impacts/m^2 s in the space region between 1 and 18 AU [45]. At mass threshold of 10^{-16} kg, detectors on Galileo and Ulysses recorded a penetration flux of 10^{-4} impacts/m^2 s in the same region [41]. We infer from these data that $\alpha = -0.5$, which is consistent with direct measurements.

We have shown that high-speed meteoroids with sizes of $0.1h$ or greater can produce expanding holes directly and must be avoided. A meteoroid with the critical size $0.1h$ has a mass of 10^{-17} kg. With such a mass threshold, previous data and Eq. (26) show a penetration flux of 10^{-4} impacts/m^2 s. Thus there will be 100 impacts per second on the space film with surface area of 1 km^2, implying a very short film lifetime. On the other hand, to achieve the desired lifetime of a few years, i.e., 10^7 s, requires a flux of 10^{-13} impacts/m^2 s or less that corresponds to a mass threshold $m \gtrsim 100$ kg. To survive impacts up to this mass threshold would require $h \approx 1$ m, which is clearly not feasible.

Thus additional manipulations must be employed to protect the film against impacts from meteoroids with size of $0.1h$ or greater. Since interplanetary dust velocities are assumed to be mainly concentrated in certain directions within the ecliptic plane of the solar system [46], one could possibly avoid major impacts by tilting the film to be tangent to the predominant meteoroid orbits and using a shield. One can also imagine modifying the film liquid so that a hole does not lead to catastrophic failure. We sketch some ideas in the Discussion section below. In what follows, we shall suppose that some means of protecting the film against rupture by micrometeoroids has been employed.

Next we assess the film mass loss due to bombardments from incoming meteoroids. We rewrite the mass flux Eq. (26) as the flux with respect to size r and greater with $\alpha = -0.5$,

$$n(r) = n_0\left(\frac{r}{r_0}\right)^{-3/2}, \tag{27}$$

where r_0 is the size of the meteoroid with mass m_0. The flux of meteoroids between size r and $r+dr$ is then $-(dn/dr)dr = n_0(r/r_0)^{-5/2}dr/r_0$. If each incoming meteoroid of size r knocks out a column of film liquid with area $\pi(10r)^2$, then the total mass loss flux due to bombardments from meteoroids up to size r_M is

$$\phi_M \approx \rho h \int_0^{r_M} 100\pi r^2(-(dn/dr))dr = 200\pi\rho h r_M^2 n(r_M). \tag{28}$$

If we set the cutoff size r_M to be 1 m which, as shown above, corresponds to 1 impact per year on the entire film, we find $\phi_M \approx 10^{-13}$ kg/m^2 s. ϕ_M is thus much smaller than the requisite evaporation flux ϕ [Eq. (6)], and the mass loss due to meteoroid bombardments is negligible.

V. TWO-DIMENSIONAL HYDRODYNAMICS AND TURBULENCE

Two-dimensional hydrodynamics and turbulence have attracted sustained scientific attention [47]: they are the basic model for geophysical and planetary flow, and are relevant to the large-scale dynamics of ocean and atmosphere, and are also applied to strongly magnetized plasmas.

Mathematically two-dimensional hydrodynamics is governed by the incompressible Navier-Stokes equation

$$\partial_t \mathbf{v} + \mathbf{v}\cdot\nabla\mathbf{v} = -\nabla p + \frac{\eta}{\rho}\nabla^2\mathbf{v} \tag{29}$$

for the velocity field $\mathbf{v}$, where p is a pressure field chosen so that $\nabla\cdot\mathbf{v} = 0$, and ρ is the density, and η is the dynamic viscosity. "Two-dimensional turbulence" corresponds to high Reynolds number solutions of the Navier-Stokes equation that depend only on two Cartesian coordinates [48]. In this case, it is straightforward to verify that the component of the velocity along the third coordinate axis satisfies an advection-diffusion equation and decouples from the horizontal flow.

Both theoretical models [49] and experimental measurements [50] show that two-dimensional turbulence has a unique "double cascades" structure: enstrophy (mean-square vorticity) is transported *downward* from the injection scale to the viscous scale, while energy is transported *upward* from the injection scale to a larger scale imposed by the boundary of the system. The transfer of enstrophy or energy is *inertial* in these ranges without loss. The upward cascade of energy consequently gives rise to mergers of vortices and hence the emergence of large-scale coherent patterns compatible with the boundary where the energy eventually dissipates. Thus two-dimensionality imposes additional boundary conditions on the flow. This could be relevant to the geometry of our proposed space film experiment.

For a film configured as a thin layer of base liquid between two layers of surfactants, some modifications to the theory need to be introduced [51]. First, the pressure term in Eq. (29) is incomplete. The surface tension becomes more important as the film gets thinner. For a thin film with thickness h, the pressure p is replaced by the surface tension term σ/h. Second, the surfactant layers modify the film viscosity in such a way that they bring about additional dissipation that characterizes the viscous friction in the film plane. This additional dissipative force can be formulated as

$$F_s = 2\frac{\eta_s}{\rho h}\nabla^2 \mathbf{v}, \tag{30}$$

where ρ is the liquid density, and η_s is the surface viscosity of the two surfactant layers. η_s is determined by the nature of the surfactant and film liquid, and it also depends on surfactant concentration. In the case of soap films, η_s/h is comparable to the dynamic viscosity of water [51], but more general data for η_s are not available.

The effective dynamic viscosity of a thin liquid film is therefore

$$\eta_f = \eta + 2\frac{\eta_s}{h}, \tag{31}$$

where η is the dynamic viscosity of the base liquid. The Reynolds number for the two-dimensional flow in such a film is

$$\mathrm{Re} = \frac{\rho U l_{\mathrm{inj}}}{\eta + 2\eta_s/h}, \tag{32}$$

where l_{inj} is the energy injection length scale at which the system is driven.

We now assess the highest Reynolds number attainable for the space film by estimating the nominal flow velocity U. Since the film is thin, the stability of the film is dependent on surface forces. Pieces of the film have a typical lateral velocity that must go to zero as the pieces approach the boundary. This process could cause the accumulation of liquid in the local region and variance in film thickness, and it could damage the film. Any thickening of the film requires a potential flow such that $\boldsymbol{\nabla}\cdot\mathbf{v} \neq 0$ as discussed after Eq. (18). Such a flow causes compression of the surfactant layer and a compressive stress Π due to the resulting gradient in surface concentration of surfactants. It is the compressive stress that stops the flow towards the boundary. Since the stress is determined by the nature of the surfactants and the film liquid, this process limits the velocity in a range that is compatible with the film to prevent the film from bulging significantly into the third dimension, and this force is provided by surface tension.

For a film patch of unit area moving with the nominal velocity U, the required decelerating force is

$$h\rho\frac{dU}{dt} = h\rho\frac{dU}{dx}\frac{dx}{dt} = h\rho\frac{d(U^2/2)}{dx}. \tag{33}$$

This force is provided by the gradient of the compressive stress $d\Pi/dx$, and therefore

$$\Delta\Pi \approx \tfrac{1}{2}h\rho U^2. \tag{34}$$

We can estimate $\Delta\Pi$ by considering the difference in surface tension with and without surfactants, i.e.,

$$\Pi \sim \sigma - \sigma_\Gamma. \tag{35}$$

Since $\Delta\Pi \lesssim \Pi$, $\Delta\Pi$ is thus smaller than σ. And since σ_Γ provides the restoring force preventing the film from bulging, σ_Γ cannot be too small. We can therefore assign $\Delta\Pi$ as a finite fraction of σ such as 1/2, and thus

$$U \approx \sqrt{\frac{\sigma}{\rho h}} \sim 1\ \mathrm{m/s}. \tag{36}$$

The highest Reynolds number for the film based on DC 705 liquid is

$$\mathrm{Re} \approx \frac{\rho U L}{\eta} \sim 10^7, \tag{37}$$

where we have ignored the surface viscosity [Eq. (32)] and have chosen l_{inj} to be its maximum value, the system size L [79].

We have seen that the surfactants retard but do not eliminate divergence in the two-dimensional flow, creating a variable thickness. These flows create additional dissipation not accounted for by bulk or surface viscosity. This dissipation could significantly reduce the Reynolds number though we are unable to estimate it here. Moreover, the above analysis is based on conventional thin-liquid-film model, and it may not be applied to other stable film configurations such as the "black film" that we shall discuss in the Discussion section.

In a normal laboratory environment, high pressure air in a wind tunnel [80], or fluids with extremely low viscosity, such as liquid helium [52,53], are used to achieve high Reynolds numbers up to 10^7. These methods only apply to the three-dimensional turbulence, however. Our result Eq. (37) is thus comparable to the highest Reynolds number achievable in normal laboratories.

Besides potentially achieving very high Reynolds number, the space film also lasts for a comparatively long time. This feature can be very important for the experimental study of turbulence. Turbulence can be divided into two types [6]: forced steady-state turbulence and decaying turbulence. For forced turbulence the two-dimensional flow is constantly stirred by a stirring device, and for decaying turbulence the system is stirred at the beginning, and then the stirring device is removed. High Reynolds number is more desirable in the first case since we are interested in properties of the steady state. In the decaying turbulence case, the whole dynamics is important, and the time scale needs to be long enough to allow the dynamics to fully develop. In principle, both types of turbulence can be realized in the space film.

VI. COMPARISON WITH OTHER RECENT EXPERIMENTS ON TWO-DIMENSIONAL HYDRODYNAMICS

Current experimental studies of two-dimensional hydrodynamics and turbulence are based on two different realizations [6]. The first approach is to use soap films to model two-dimensional flows. Turbulent flows are generated by dragging thin objects along film surfaces [51,54]. The problem with this method is that the air near the film surfaces affects the flow, and additional viscous friction needs to be included in order to understand the dynamics [55]. The second approach is to use shallow layer of solution to approximate the quasi-two-dimensional flow [56,57]. Electromagnetic forces are used to make the solution flow. The difficulty with this method is that the depth of the fluid layer and the friction from the bottom of the cell affect the dynamics [58].

Therefore in the normal laboratory environment, it is very difficult to completely decouple the two-dimensional flow with the solid surfaces or the gaseous phase that surrounds it [55]. The attainable Reynolds number in current experimental studies of two-dimensional turbulence is of the order of 10^4 due to technical restrictions [59,81].

To compare with the space film, we focus on current experimental studies based on soap films. Some important developments have been reported recently. In the soap tunnel device [60], the maximum film speed is 30 cm/s for a film with thickness of 6 μm. In the flowing film method [61], the whole film is falling, and new fluid is supplied at the top. A maximum velocity of a few meters per second is achieved. However since the film is falling fast, its width and thickness are difficult to control. Most recently some improvements of the falling film experiment have been made [62], and two-dimensional nonlinear dynamics has been studied with improved experimental techniques. The flow speed in such falling films ranges between 0.5 and 4 m/s, with film thickness between 1 and 10 μm, and typical film size of 3 m tall and 10 cm wide. Giant films, with size as large as 10 m, are also achievable with similar techniques. The Reynolds number for giant films is about 10^6. No experimental results on such giant films have been reported, however.

The soap-film-based experiments have some common restrictions. First, as mentioned before, the dragging force due to the air near the film can never be totally eliminated, and this additional viscous friction affects the two-dimensional nonlinear dynamics. Second, since static large films cannot last long under normal laboratory conditions due to the drainage of gravity, these films are necessarily falling vertically with base liquid perpetually injected into the system. Two-dimensional nonlinear dynamic processes with time scale longer than the characteristic time of the falling system cannot fully develop in such films.

Compared to these realizations, the space film can potentially achieve considerably higher Reynolds number, with much larger lateral dimension, and last for a much longer time scale. External forces are needed in order to accelerate the base liquid to its nominal velocity of 1 m/s, which is comparable to those typical velocities achieved in conventional soap films.

VII. FORCES ON THE SPACE FILM

A. Support force

The space film needs to be supported by a frame. The frame should support the film tension and the force due to the base liquid flow: the frame must provide a force to decelerate the liquid near the boundary. According to our previous analysis, when the system achieves its nominal velocity, i.e., $U=1$ m/s, these two forces are comparable to each other and can be estimated as

$$F=\sigma L=10\text{ N}. \tag{38}$$

A light frame can easily support such a small force. In addition, the frame must also be strong enough against buckling.

B. External forces

The film encounters perturbing forces from the space environment. These forces should not perturb the film too much. On the other hand, deliberate forcing is needed in order to create the desired turbulent flow. We consider each type of force in turn.

1. Environmental forces

Radiation pressure. The solar radiation flux at the earth orbit is 1.37×10^3 W/m^2 [15]. The corresponding momentum flux is 10^{-5} Pa, and the total force on the film is no more than 10 N. This force is comparable to the characteristic dynamic force [Eq. (38)].

Solar wind pressure. The solar wind pressure due to incoming charged particles is of the order of 10^{-9} Pa [15] and is negligible compared to the radiation pressure.

Electrostatic force. In the space environment the film is charged, and it can interact with the ambient electric field. The incoming charged particles can charge the film to as high as 10 V [63]. This finding is comparable to the approximation by using image charge attraction (we assume the attraction potential to be that of two elementary charges at an atomic separation). We can estimate the charge of the film via the formula $V_e=(1/4\pi\epsilon_0)(Q/L)$. We set V_e to be 10 V and find $Q=10^{-6}$ C. If we assume the moving electric field to be a few millivolt per meter that is the characteristic field of the ionosphere, it gives a total force 10^{-9} N. Again this force is very small and is negligible compared to other forces.

Marangoni forces. One can achieve a desired tangential gradient of surface tension along the film surface via a nonuniform temperature. The resultant Marangoni forces could be the driving force. Nonuniformity in surfactant concentration can also yield variations in surface tension. Moreover, external perturbations and hydrodynamic flow can induce variations in thickness [64], which will introduce additional Marangoni-type forces. Further study of Marangoni forces on the space film is needed for the film design.

2. Direct mechanical forces

The forces needed to generate the turbulent flow can be supplied mechanically or via electromagnetic forces. These forces should not be larger than the characteristic force, i.e., 10 N. We may use existing soap-film experiments as a guide in implementing these forces. We may, for example, insert a mechanical stirrer into the film [62]. The stirrer could be supported by wires suspended above the film. It could be driven by conventional electric motors. The size and motion of the stirrer determine the energy injection length scale l_{inj}. In the same manner, the flow could be observed by conventional cameras also suspended above the film. Detailed analysis and design of these forces involve technical and engineering issues that go beyond the scope of this paper.

VIII. CHARACTERISTIC TIMES

Besides the lifetime and the previously discussed time to freeze, there are other time scales that are relevant to the two-dimensional dynamics in the film and are important for film design.

Acceleration time. The acceleration force should not be larger than the characteristic force, i.e., 10 N, otherwise the surface tension will not be able to sustain the system. If the acceleration force is 1 N and the total mass of the film is 10^3 kg, the acceleration will be 10^{-3} m/s^2. It will take 10^3 s to accelerate the system to its nominal velocity $U=1$ m/s.

Transit time. The transit time is $L/U \approx 10^3$ s for the liquid to flow from one side to the other side of the film. The experiment needs to last many transit times for the film to reach the steady state. The transit time provides the lower bound for the film lifetime. Our original designed lifetime of 1 year readily satisfies this condition.

Relaxation time. In connection to the double-cascade structure, two-dimensional turbulence first relaxes to a metaequilibrium state with the emergence of large-scale coherent patterns and little energy loss, and the metaequilibrium state then decays through the energy dissipation at the boundary [65,66]. In the decay of the metaequilibrium state, we assume the shear rate to be of order U/L. The total power dissipated by the viscous force is thus $P_\eta \approx \eta U(U/L)Lh = \eta U^2 h \approx 10^{-5}$ W. The viscous relaxation time is defined to be the total kinetic energy of the film divided by the total power due to the viscous force,

$$\tau_\eta = \frac{K}{P_\eta} \approx \frac{MU^2}{2\eta U^2 h} = \frac{M}{2\eta h}, \tag{39}$$

and we find $\tau_\eta \approx 10^{10}$ s. τ_η is longer than the designed lifetime of 1 year, and thus the relaxation process cannot be established during the experiment.

Assembly time. Although we do not discuss assembly of the film in this paper, we may still consider the restrictions on the assembly time. To keep the fluid stationary during the assembly precess, the speed of the enlargement of the film should be much less than the characteristic speed 1 m/s. If we use the velocity $v=0.1$ m/s, it takes $L/v=10^4$ s to assemble the system. The actual process can be much slower due to mechanical complexities.

IX. DISCUSSION

For concreteness we have assumed in our derivation a specific base state of the system. From the outset we fixed the film thickness, lateral dimensions, and the expected lifetime. We also chose a particular liquid. However, our estimates may be used much more generally. We have shown how each of our quantities depends on the parameters, so that it is a simple matter to infer the effect of an order-of-magnitude reduction in lateral dimension. This will reduce the achievable highest Reynolds number according to Eq. (37), but it will reduce the effect of meteoroid impacts, and it is more technically feasible. Also, larger surface tension and smaller viscosity are advantageous from the perspective of two-dimensional hydrodynamics. Surface tension and viscosity are limited by the choice of the liquid, however. In principle, we can choose the base liquid with the lowest possible viscosity that is allowed by the acceptable lifetime [Eq. (15)].

Regarding the film stability against spontaneous rupture, we have based our estimates entirely on the standard stability analysis. Alternatively, we may consider a different realization of the stable film configuration, i.e., a "black film"[14,67]. Although both theoretical and experimental studies on such films have been limited to microscopic bounded films with typical size of a few hundred micrometers [14], we think they could be relevant to our space film experiment. Especially near the boundary where the space film is supported by the external frame, microscopic theory applies. A sharp transition from an unstable thinning film to a stable black film may occur at critical film thickness of a few hundred angstroms. In forming the stable black film, the electrostatic disjoining pressure due to the repulsive force between the charged surfactant layers on the two film surfaces contributes to the stability. In addition to this long range force, the short-range interactions in the adsorption layers are crucial: the formation of black films depends on the surfactant type and concentration. The black films are notably much thinner than the films we have considered under our standard conditions, and thus much less liquid is needed to form the black films. On the other hand, smaller thickness makes the film more vulnerable to external impacts and reduces the film lifetime against evaporation [Eq. (5)]. Thus we see no clear-cut advantage to the black films. Moreover, the feasibility of creating a stable black film in our situation is not clear. In the nonaqueous liquids we are obliged to use, the prospects for the charged surfaces are much reduced, and thus a stable black film may not be attainable. Furthermore, there are no assurances that two-dimensional flows with high enough Reynolds number can be achieved in black films. Further analysis and investigations of these liquids and their surfactants are needed in order to address these problems.

A simple film is subject to catastrophic failure when penetrated by micrometeoroids, and this vulnerability to meteoroids is the chief stumbling block of our scheme. Thus it is desirable to find a means to arrest the growth of holes caused by meteoroids. One can imagine designing a liquid film with this self-healing property. For example, a liquid that immediately solidified in the vicinity of a small hole would arrest the further opening of the hole. To achieve this solidification, the liquid would have to contain molecules that could crosslink the base liquid. The reaction might be triggered by the energy dissipation of the passing meteoroids. The reaction would have to stop after solidifying a small region around the hole, so that only a small solid island remained in the film, and its overall fluidity was little affected. This scheme appears difficult to achieve but not impossible. Further, recent experiments [68] showed that millimeter-scale projectiles at impact speed of 1 m/s may sail through the thin film without leaving a hole due to the pinch-off effect. These low-velocity results could be relevant in finding effective ways to protect the space film from micrometeoroids.

Although the potential to achieve a high Reynolds number is one of the most prominent advantages of the space film experiment, the space film platform brings other advantages as well. The spatial extent of these films may greatly exceed the size of terrestrial soap films, even at a size much smaller than our assumed size of one kilometer. Such films may offer advantages for studying flow phenomena that require long observation times but not unprecedented Reynolds numbers. Moreover, the space film can be also useful to space science itself. Being subject to the external impacts and ambient forces, these films could be the basic tools to observe and measure such interplanetary dynamic phenomena as solar wind and cosmic dusts.

Further, although we consider in this paper large-scale thin-film experiment based on liquids, we can also imagine similar experiments with solid soft material sheets of large spatial extent in the space environment. Compared to thin liquid films, such sheets will have less restrictions. The space environment allows unprecedented size-to-thickness ratio and permits elastic stress concentration to occur with little disturbance from other forces [69]. It is important to understand the motions and deformations of large sheets subject to the ambient conditions in the space environment.

The space film experiment also challenges current space technology. Further researches and experiments need to be carried out in order to launch and assemble the system, to observe and measure the system, and to repair and maintain the system. Similar space programs currently underway suggest that these logistical challenges are surmountable. For instance, the recent solar film or space sail experiment that deploys large-scale light solid sheets has similar properties to our proposed space film, and begins to explore these techniques [70,71]. Both the space sail and our proposed film experiments involve launching and deploying kilometer-scale sheets of light materials with total weight up to a metric ton, and maintaining the system in the interplanetary environment for years. We can thus imagine to achieve significant synergies in technologies and resources among those similar space programs.

X. CONCLUSION

As we have shown, space environment imposes strict conditions on thermodynamical and other physical properties of large-scale thin liquid films. Various issues and parameters, such as the film viscosity, vapor pressure, and compatible surfactants, need to be carefully designed and experimentally tested to achieve required stability and other desired properties. We found that despite many potential obstacles to realizing square-kilometer thin films, only the meteoroid impacts seemingly make large films unfeasible. Some way, such as a shield or a self-healing mechanism in film fluid, must be found to prevent meteoroids from destroying the film. Alternatively we must restrict ourselves to much smaller films, and thus we must consider possible applications of the space film to the study of two-dimensional flows of lower Reynolds number.

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APPENDIX: POSSIBLE CANDIDATE BASE LIQUIDS

Dow Corning 705 (DC 705) pump oil (penta-phenyl-tri-methyl-tri-siloxane) is a colorless to straw colored, single component fluid designed for ultrahigh vacuum applications. Composed of relatively small molecules in the form of short three-monomer chains ($N=3$), it has the highest phenyl content among all DC pump oil products and hence the lowest vapor pressure. Its typical physical and chemical properties are [13]

Extrapolated vapor pressure, torr, at 298 K	3×10^{-10}
Specific gravity at 298 K	1.09
Viscosity at 298 K, cSt	175
Flash point, open cup, K	516
Boiling point, at 0.5 torr, K	518
Typical boiler temperature K	523–543
Surface tension, dyn/cm	36.5
Heat of vaporization, kcal/g mol, at 523 K	28.2
Molecular weight	546

Using these data, stability analysis [Eq. (15)] gives a rupture time of 100 years, with proper surfactants added. The typical vapor pressure, however, is still larger than our earlier estimate [Eq. (12)] against evaporation.

Vapor pressure can be reduced by lowering temperature. According to the empirical vapor pressure equation for DC 705 pump oil [13]

$$\log_{10} P/\text{torr} = 12.31 - \frac{6490}{T/\text{K}}, \tag{A1}$$

we find condition (12) can be satisfied at about 273 K.

To change the temperature will affect the viscosity. Because of their high phenyl content, pump oils show great change in viscosity with temperature [72]. In the case of DC 705 pump oil, the viscosity increases from 175 cSt at 298 K to 10 000 cSt at 273 K. Lowering temperature thus drastically reduces the film fluidity and should be avoided.

The great sensitivity of viscosity to temperature is an unwelcome property, and efforts must be made to keep the film temperature stable. Meanwhile, we can reduce this sensitivity by lowering the phenyl content. For comparison, we have also considered poly-dimethyl-siloxane, or PDMS. No series of organic liquids show as little change in viscosity with temperature as PDMS [72]. PDMS are listed as DC 200 fluids, and their viscosity at 298 K ranges from 0.65 cSt to 10^6 cSt with respect to different molecular chain lengths. We have particularly considered the PDMS fluid with viscosity 1000 cSt, which has a molecular weight of 16 500. Using available data [73], we infer that at 273 K it has a vapor pressure of 10^{-3} torr, which is far too high compared to the condition Eq. (12).

In principle other silicones with low or medium phenyl content can be also considered as candidate base liquids.

They have lower vapor pressure compared to DC 200 fluids, and their viscosity is not as sensitive to temperature as DC 705 fluid.

We can also reduce the vapor pressure by increasing the number of units N. As shown previously, condition (12) can be satisfied with $N=4$. To change the molecular weight will also affect the viscosity. According to the empirical relation [74]

$$\eta \propto M^3, \tag{A2}$$

we find for $N=4$ the viscosity increases only modestly to about 450 cSt, which is still feasible.

[1] A. Oron, S. H. Davis, and S. G. Bankoff, Rev. Mod. Phys. **69**, 931 (1997).
[2] A. Oron, Eur. Phys. J. E **12**, 455 (2003).
[3] J. Becher *et al.*, Nat. Mater. **2**, 59 (2003).
[4] V. Ya. Shkadov, M. G. Velarde, and V. P. Shkadova, Phys. Rev. E **69**, 056310 (2004).
[5] *Thin Liquid Films: Fundamentals and Applications*, edited by I. B. Ivanov [Surfactant Science Series **29** (1988)].
[6] H. Kellay and W. I. Goldburg, Rep. Prog. Phys. **65**, 845 (2002).
[7] *Physics of Fluids in Microgravity*, edited by R. Monti (Taylor & Francis, New York, 2001).
[8] J. Miller, Phys. Rev. Lett. **65**, 2137 (1990).
[9] R. Robert and J. Sommeria, J. Fluid Mech. **229**, 291 (1991).
[10] S. Ostrach, Annu. Rev. Fluid Mech. **14**, 313 (1982).
[11] *Advances in Fluid Turbulence: Proceedings of the Eighth Annual International Conference of the Center for Nonlinear Studies*, edited by G. Doolen *et al.*, reprinted from Physica D **37** (1988).
[12] A. Sharma and E. Ruckenstein, Langmuir **2**, 480 (1986).
[13] Product information for Dow Corning 705 diffusion pump oil, Form No.10–838–98, Dow Corning Corporation, 2200 W. Salzburg Rd., Midland, MI 48640-8531, 1998.
[14] E. D. Manev and A. V. Nguyen, Adv. Colloid Interface Sci. **114-115**, 133 (2005).
[15] Natural orbit environment guidelines for use in aerospace vehicle development, edited by B. J. Anderson, NASA TM 4527, 1994.
[16] *Handbook of Chemistry and Physics*, 85th ed., edited by D. R. Lide *et al.* (CRC, Boca Raton, 2004).
[17] MODIS UCSB Emissivity Library.
[18] M. W. Zemansky, *Heat and Thermodynamics* (McGraw-Hill, New York, 1951).
[19] P. W. Atkins, *Physical Chemistry*, 7th ed. (Oxford University Press, Oxford, 2001).
[20] M. Prevost and D. Gallez, J. Chem. Phys. **84**, 4043 (1986).
[21] S. G. Yiantsios and B. G. Higgins, J. Colloid Interface Sci. **147**, 341 (1991).
[22] A. De Wit, D. Gallez, and C. Christov, Phys. Fluids **6**, 3256 (1994).
[23] A. Sharma *et al.*, Phys. Fluids **7**, 1832 (1995).
[24] H. Fijnaut and A. Vrij, Nature (London), Phys. Sci. **246**, 118 (1973).
[25] D. Goodall *et al.*, Colloids Surf. **43**, 41 (1988).
[26] E. Goldschmidt, Stability of free thin liquid films in microgravity environment, Research Experience for Undergraduates project report, The University of Chicago, 2003.
[27] *Thin Liquid Film Phenomena*, edited by W. B. Krantz *et al.*, AIChE Symp. Ser. No. 252 (American Institute of Chemical Engineers, Washington, DC, 1986).
[28] T. F. Tadros, *Applied Surfactants: Principles and Applications* (Wiley-VCH, New York, 2005).
[29] O. K. Matar, Phys. Fluids **14**, 4216 (2002).
[30] L. Schramm and S. Kutay, in *Surfactants: Fundamentals and Applications in the Petroleum Industry*, edited by L. Schramm (Cambridge University Press, Cambridge, 2000), p. 79.
[31] N. V. Priezjev, A. A. Darhuber, and S. M. Troian, Phys. Rev. E **71**, 041608 (2005).
[32] A. Holmes-Siedle and L. Adams, *Handbook of Radiation Effects*, 2nd ed. (Oxford University Press, Oxford, 2002).
[33] DOE Technical Standards, DOE-HDBK-1017/-93.
[34] Lord Rayleigh, Proc. R. Soc. London **13**, 261 (1891).
[35] G. Debregeas, P. Martin, and F. Brochard-Wyart, Phys. Rev. Lett. **75**, 3886 (1995).
[36] F. E. C. Culick, J. Appl. Phys. **30**, 1950 (1959).
[37] *Handbook of Shock Waves*, edited by G. Ben-Dor *et al.* (Academic, New York, 2001).
[38] E. M. Shoemaker, in *The Moon, Meteorites, and Comets*, edited by B. M. Middlehurst and G. P. Kuiper (The University of Chicago Press, 1963), p. 301.
[39] Technical information, Lawrence Berkeley National Laboratory.
[40] D. E. Brownlee *et al.*, The twenty-fifth lunar and planetary science conference, Lunar and Planetary Institute, 1994, Part 1, p. 183.
[41] E. Grun *et al.*, Geophys. Res. Lett. **19**, 1311 (1992).
[42] E. Grun, Dust detection from space vehicles, in Meteoroids and Their Parent Bodies International Astronomical Symposium, edited by J. Stohl and I. P. Williams, Astronomical Institute of the Slovak Academy of Sciences, 1993.
[43] The Explore 16 micrometeoroid satellite, Supplement 3, Preliminary results for the peroid May 27, 1963, through July 22, 1963, edited by E. C. Hastings, NASA Tech. Memo. X-949, p. 1, 1964.
[44] The Explorer 23 micrometeoroid satellite-Description and results for the peroid November 6, 1964, through November 5, 1965, edited by R. L. O'Neal, NASA Tech. Note D-4248, 1968.
[45] D. H. Humes, J. Geophys. Res. **85**, 5841 (1980).
[46] I. Mann, Earth, Moon, Planets **68**, 419 (1995).
[47] R. H. Kraichnan and D. Montgomery, Rep. Prog. Phys. **43**, 547 (1980).
[48] U. Frisch, *Turbulence: The Legacy of A. N. Kolmogorov* (Cambridge University Press, Cambridge, 1996).
[49] G. K. Batchelor, Phys. Fluids **12**, 233 (1969).
[50] M. K. Rivera, W. B. Daniel, S. Y. Chen, and R. E. Ecke, Phys. Rev. Lett. **90**, 104502 (2003).
[51] Y. Couder, J. Phys. (France) Lett. **45**, 353 (1984).

[52] J. J. Niemela *et al.*, Nature (London) **404**, 837 (2000).
[53] C. J. Swanson *et al.*, J. Fluid Mech. **461**, 51 (2002).
[54] Y. Couder, J. M. Chomaz, and M. Rabaud, Physica D **37**, 384 (1989).
[55] M. J. Huang *et al.*, Phys. Fluids **16**, 3975 (2004).
[56] J. Sommeria, J. Fluid Mech. **170**, 139 (1986).
[57] O. Cardoso, D. Marteau, and P. Tabeling, Phys. Rev. E **49**, 454 (1994).
[58] H. J. H. Clercx, G. J. F. van Heijst, and M. L. Zoeteweij, Phys. Rev. E **67**, 066303 (2003).
[59] A. Leonard, *Turbulence and Its Simulation*, edited by T. Gatski (Springer, New York, 1995).
[60] M. Beizaie and M. Gharib, Exp. Fluids **23**, 130 (1997).
[61] H. Kellay, X.-I. Wu, and W. I. Goldburg, Phys. Rev. Lett. **74**, 3975 (1995).
[62] M. A. Rutgers, X. L. Wu, and W. B. Daniel, Rev. Sci. Instrum. **72**, 3025 (2001).
[63] E. C. Whipple, Rep. Prog. Phys. **44**, 1197 (1981).
[64] J. M. Chomaz and B. Cathalau, Phys. Rev. A **41**, 2243 (1990).
[65] W. H. Matthaeus *et al.*, Physica D **51**, 531 (1991).
[66] X. P. Huang and C. F. Driscoll, Phys. Rev. Lett. **72**, 2187 (1994).
[67] A. Scheludko, Adv. Colloid Interface Sci. **1**, 391 (1967).
[68] D. Quere (private communications).
[69] A. Boudaoud *et al.*, Nature (London) **407**, 718 (2000).
[70] E. Christensed *et al.*, Technical Report NASA/JPL 01-1531, 2001.
[71] D. Sleight *et al.*, Technical Report AIAA 2006-1706, 2006.
[72] R. R. McGregor, *Silicones and Their Uses* (McGraw-Hill, New York, 1954).
[73] Nondocumented Data, Dow Corning Corporation, 2200 W. Salzburg Rd., Midland, MI 48640-8531.
[74] M. Doi and S. F. Edwards, *The Theory of Polymer Dynamics* (Clarendon, Oxford, 1988).
[75] This is not a bad approximation. For instance, the emissivity of water is about 1 across thermal infrared region [17].
[76] Energy-delocalizing aromatic structural groups increase polymer stability by distributing energies of excited states. Substituents on aromatic groups that extend the delocalized bonding network are further stabilizers [33].
[77] For very viscous liquid films, with viscosity up to 10^6 cSt, the hole radius grows exponentially with time [35].
[78] We use the mean orbital velocity of the earth 29.78 km/s for the estimate.
[79] In many experiments [50] one chooses $l_{\text{inj}} \ll L$ so as to study the inverse cascade of energy mentioned earlier in this section. Nevertheless the nominal Reynolds number given in Eq. (37) shows the large range of length scales accessible to the space film experiment.
[80] Princeton Gas Dynamics Lab SuperPipe Facility. The range of Reynolds number achieved there is from 5×10^3 to 3.8×10^7.
[81] In numerical studies of two-dimensional turbulence, the highest attained Reynolds number is 10^4 to 10^5 [59].