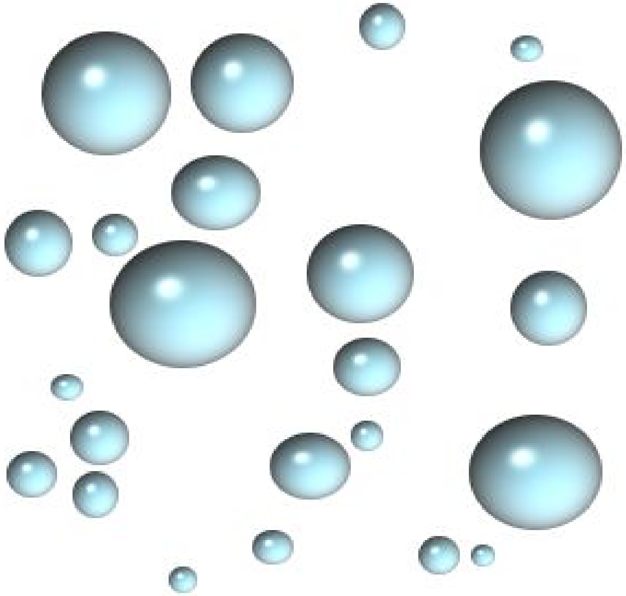



Courtesy: Images on the internet

Focus: Physics of Blowing Bubbles

February 19, 2016• *Physics* 9, 21

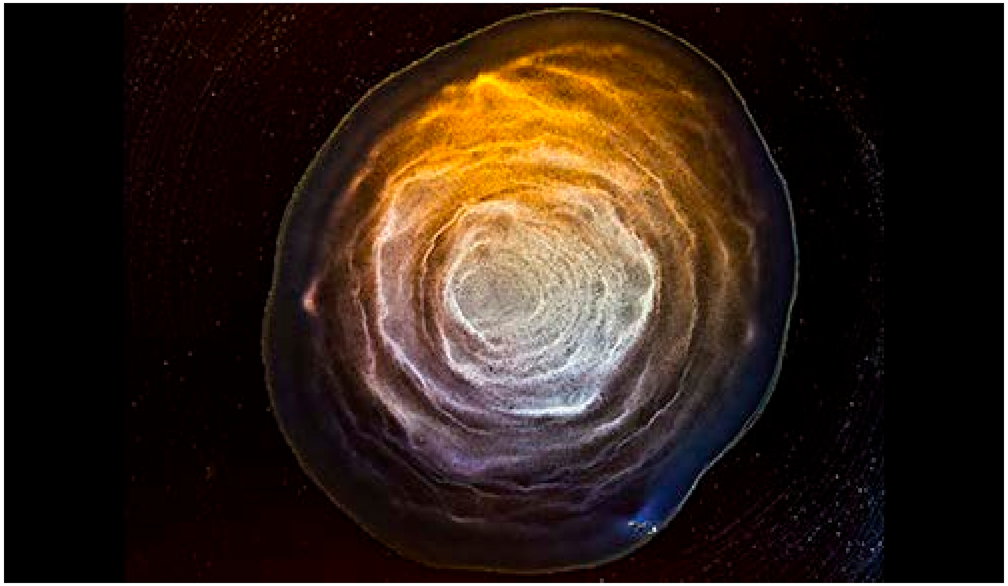
Using a bubble-blowing apparatus, researchers developed a model that explains the effects of several factors, such as the breath velocity, on the process of blowing a bubble.

Courtesy: Images on the internet

Synopsis: Whisky-Inspired Coatings

March 24, 2016

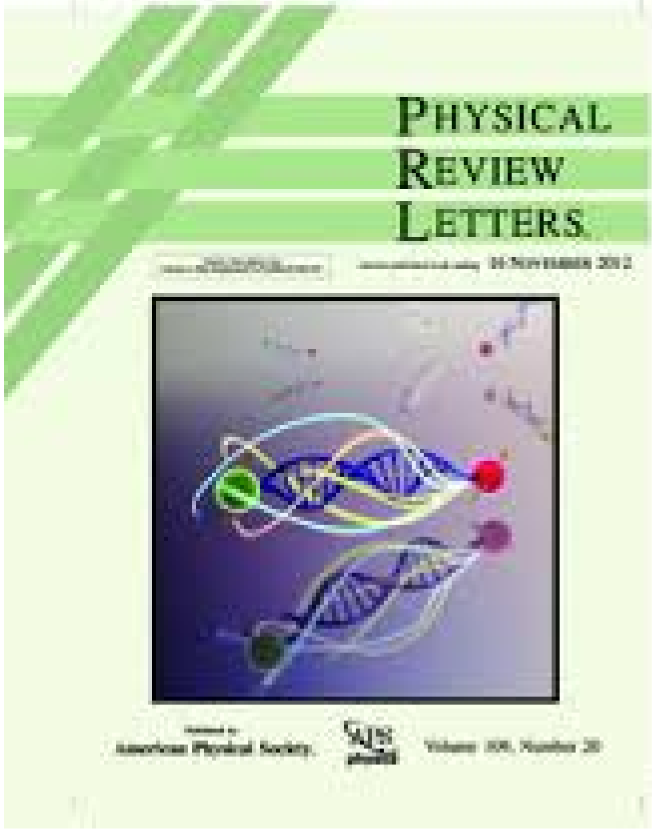
As a whisky drop dries, a combination of molecules in the liquid ensure a spatially uniform deposition—a finding that could inspire coating technologies.



Courtesy: Images on the internet

Courtesy: Images on the internet


PHYSICAL
REVIEW
LETTERS
13 AUGUST 2010
Published by the
American Physical Society
APS
physics
Volume 105, Number 7


PHYSICAL
REVIEW
LETTERS
Volume 109, Number 20

Bubbles, whisky, wine and Physical Review Letters

Manoj K. Harbola
Department of Physics
Indian institute of Technology, Kanpur

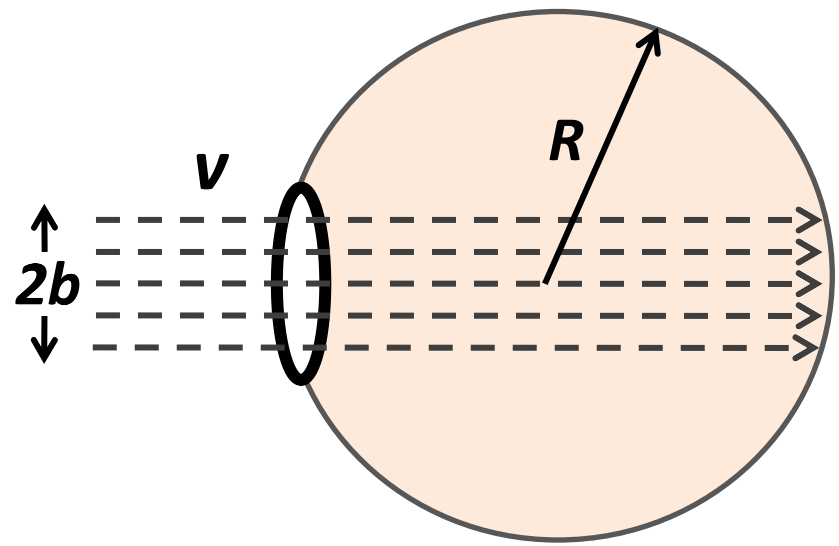
Plan of the Talk

- **Bubbles**: Formation of bubbles
- **Whiskey**: Drying of whiskey droplets
- **Wine**: Tears of wine and Marangoni effect
- **Back to Whiskey**: understanding uniform deposition pattern of whiskey droplets

1. Bubbles

A problem from the Joint Entrance Examination (JEE) - 2003

A bubble having surface tension T and radius R is formed on a ring of radius b ($b \ll R$). Air (density ρ) is blown through the ring with speed v as shown. Air stream hits the wall of the bubble perpendicularly and stops. Calculate the radius at which the bubble separates from the ring.



Understanding bubble formation

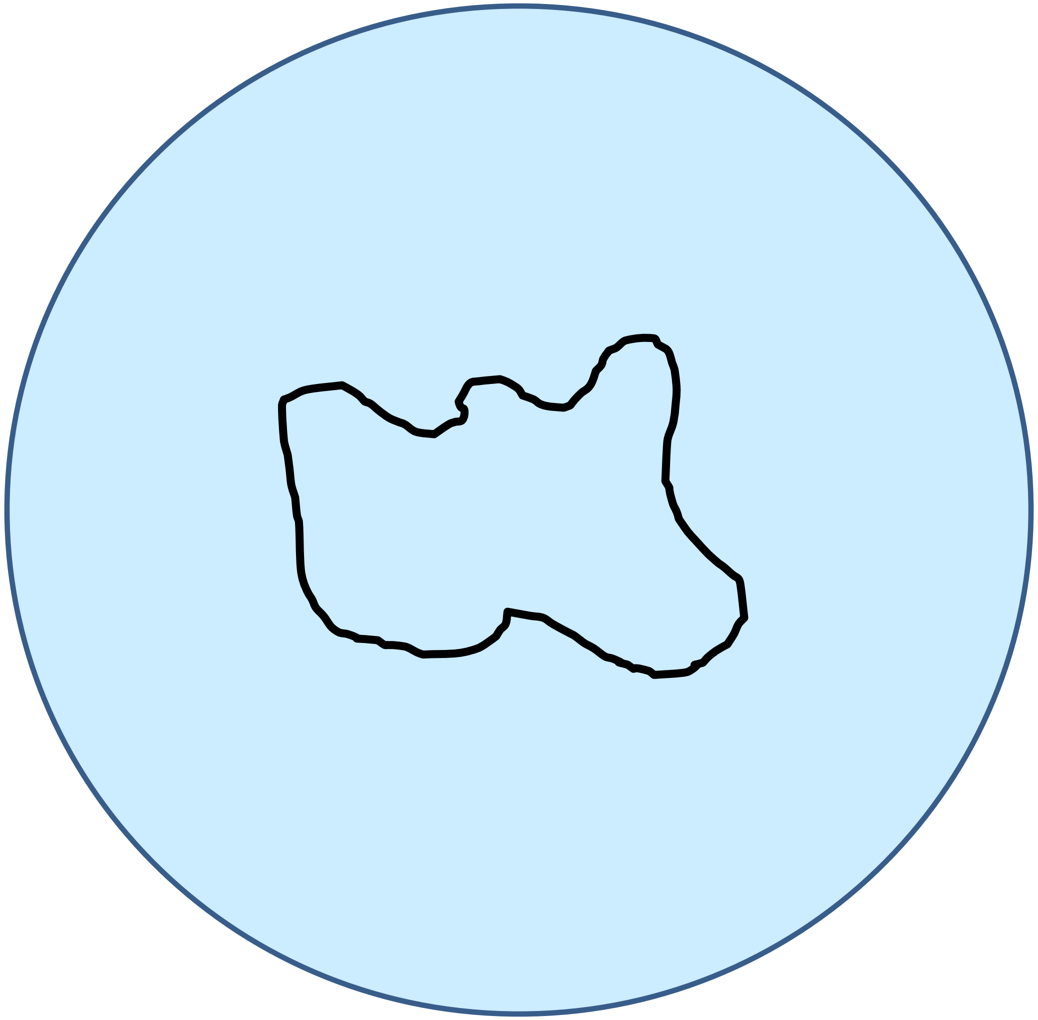
Surface Tension:

(i) Energy per unit area required to create a surface. Liquid drops are spherical because that requires least expenditure of energy;

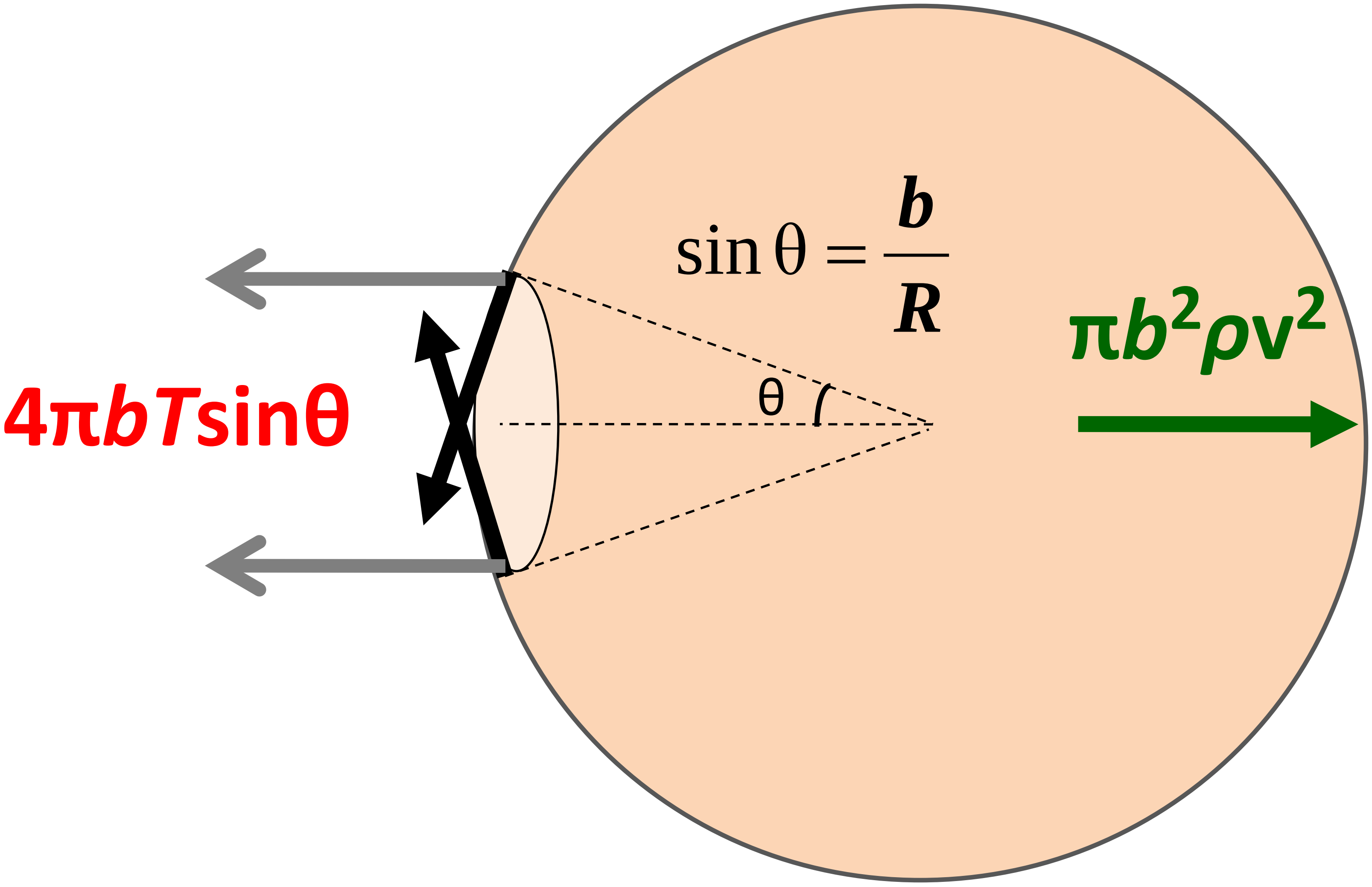
(i) Force per unit length on an imaginary line on a liquid surface.

Surface tension as a force is best observed by creating a real line (boundary) between surfaces of two liquids with different surface tension.

Understanding surface tension through a thread on water surface



Forces on the bubble



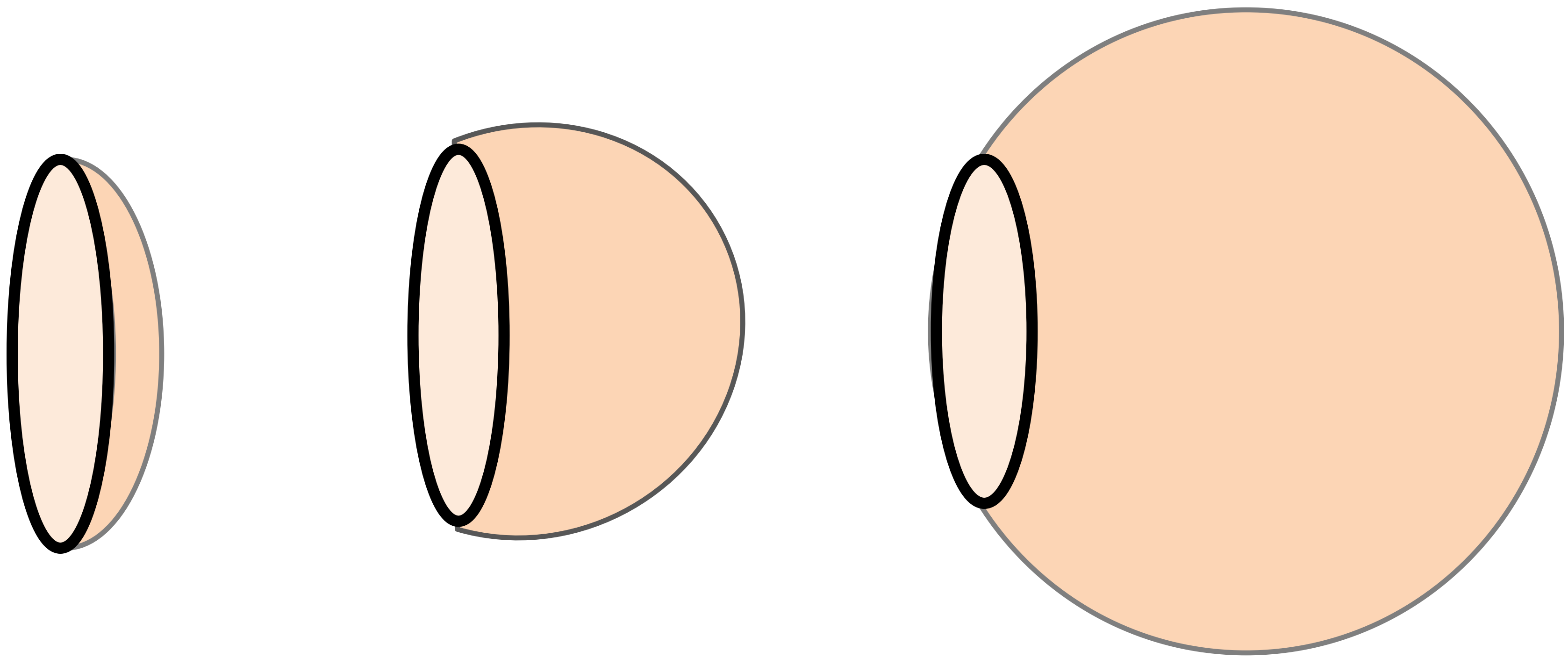
Equating the forces gives

$$\boxed{4\pi b T \sin\theta = \pi b^2 \rho v^2}$$

Substituting $\sin\theta = \dfrac{b}{R}$ leads to

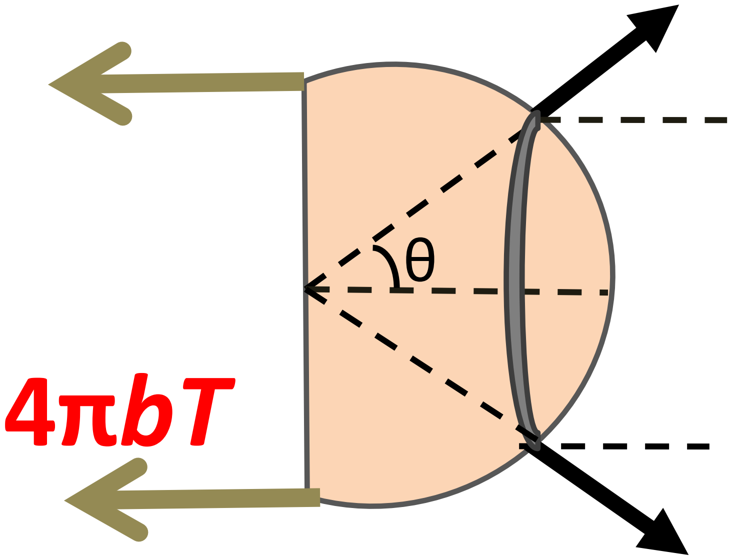
$$\boxed{R = \frac{4T}{\rho v^2}}$$

<u>Is there a minimum critical speed v_c required for bubble formation?</u>



$v < v_c$ $v \approx v_c$ $v > v_c$

Calculation of critical speed v_c



Projection of area of strip of bubble surface normal to the direction of air flow

$$\boxed{2\pi b^2 \cos\theta \, d(\cos\theta)}$$

Momentum transfer normal to the bubble surface

$$\boxed{2\pi b^2 \rho v_c^2 \cos^2\theta \, d(\cos\theta)}$$

Net horizontal force due to air flow

$$\boxed{2\pi \boldsymbol{b}^2 \boldsymbol{\rho} \boldsymbol{v}_c^2 \int_0^1 \cos^3\theta \, d(\cos\theta) = \frac{\pi}{2} \boldsymbol{b}^2 \boldsymbol{\rho} \boldsymbol{v}_c^2}$$

Equating the opposing forces due to surface tension and due to air flow gives the critical speed

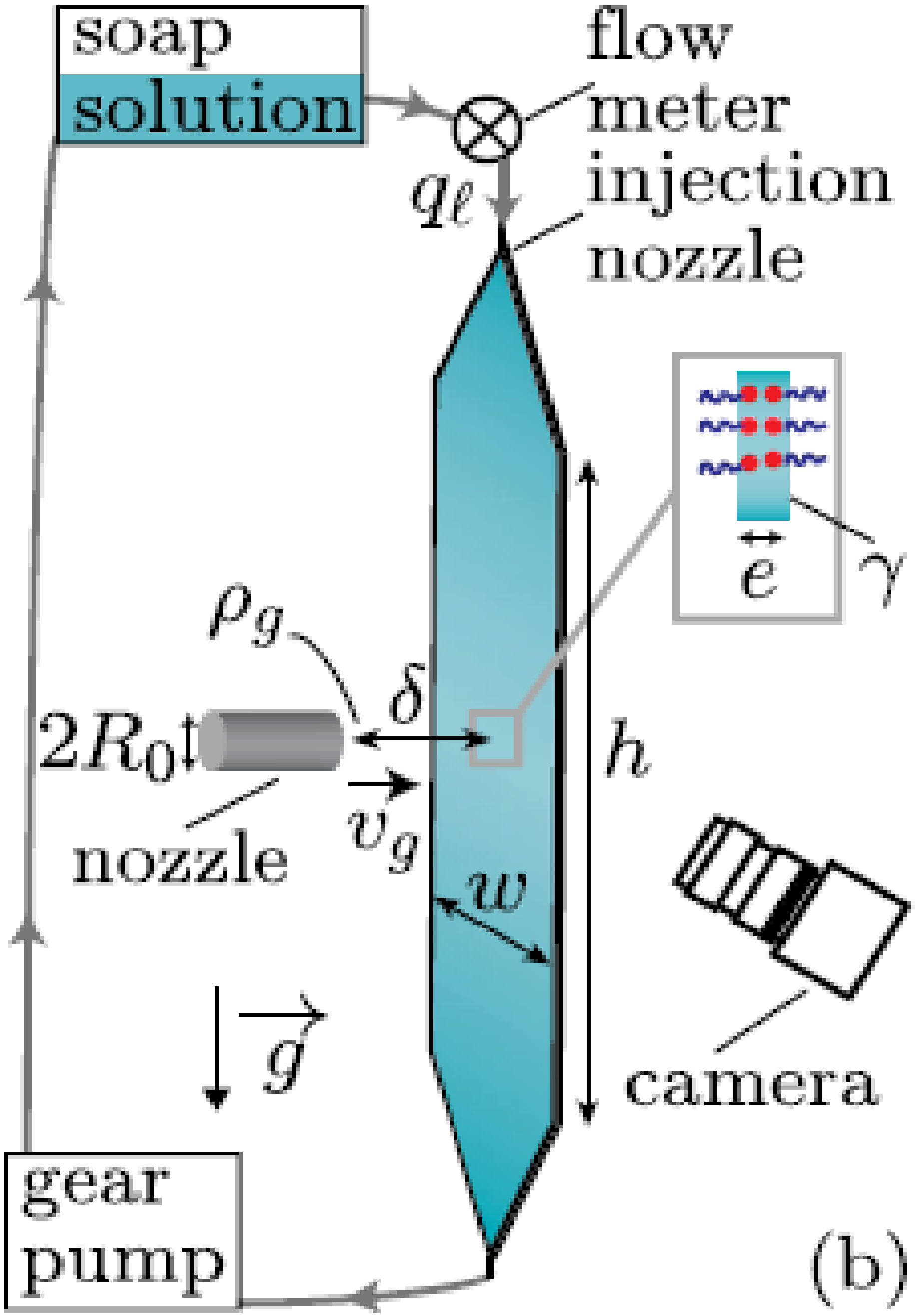
$$\boxed{V_c = \sqrt{\frac{8T}{b\rho}}}$$

Experimental verification

Generating Soap Bubbles by Blowing on Soap Films

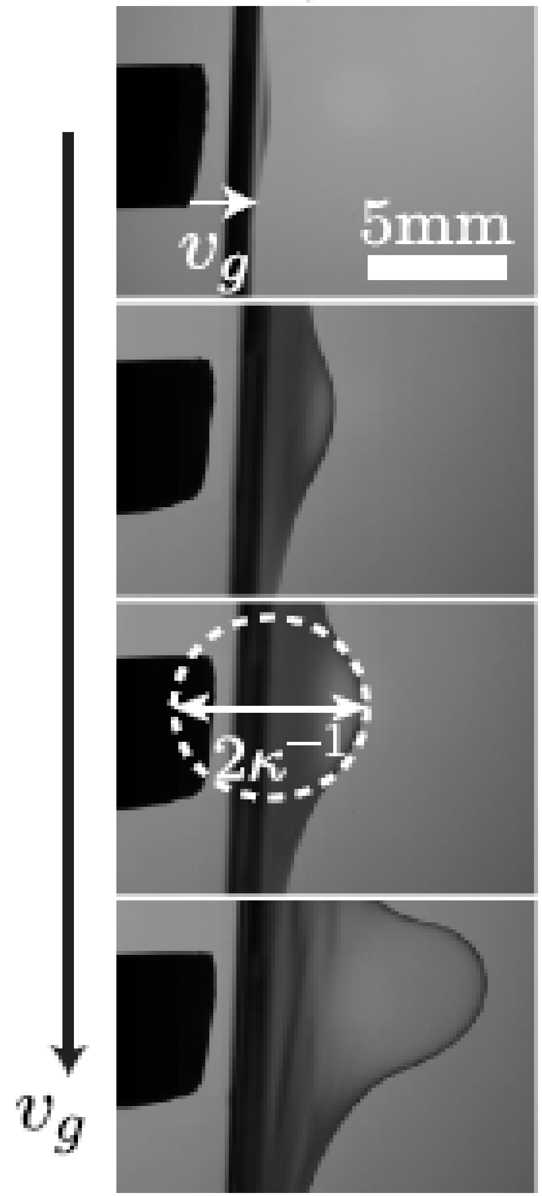
Physical Review Letters 116, 077801 (2016)

Louis Salkin, Alexandre Schmit, Pascal Panizza,* and Laurent Courbin†

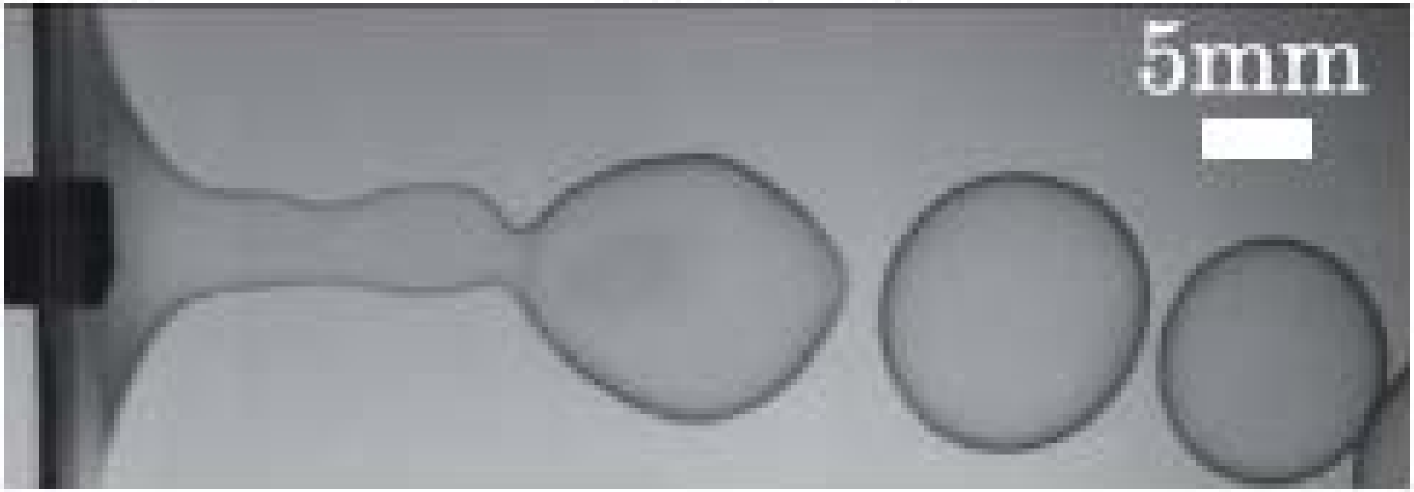


soap
solution
flow
meter
q_ℓ
injection
nozzle
e
γ
ρ_g
δ
$2R_0$
v_g
nozzle
w
h
$\vec{g}$
camera
gear
pump
(b)

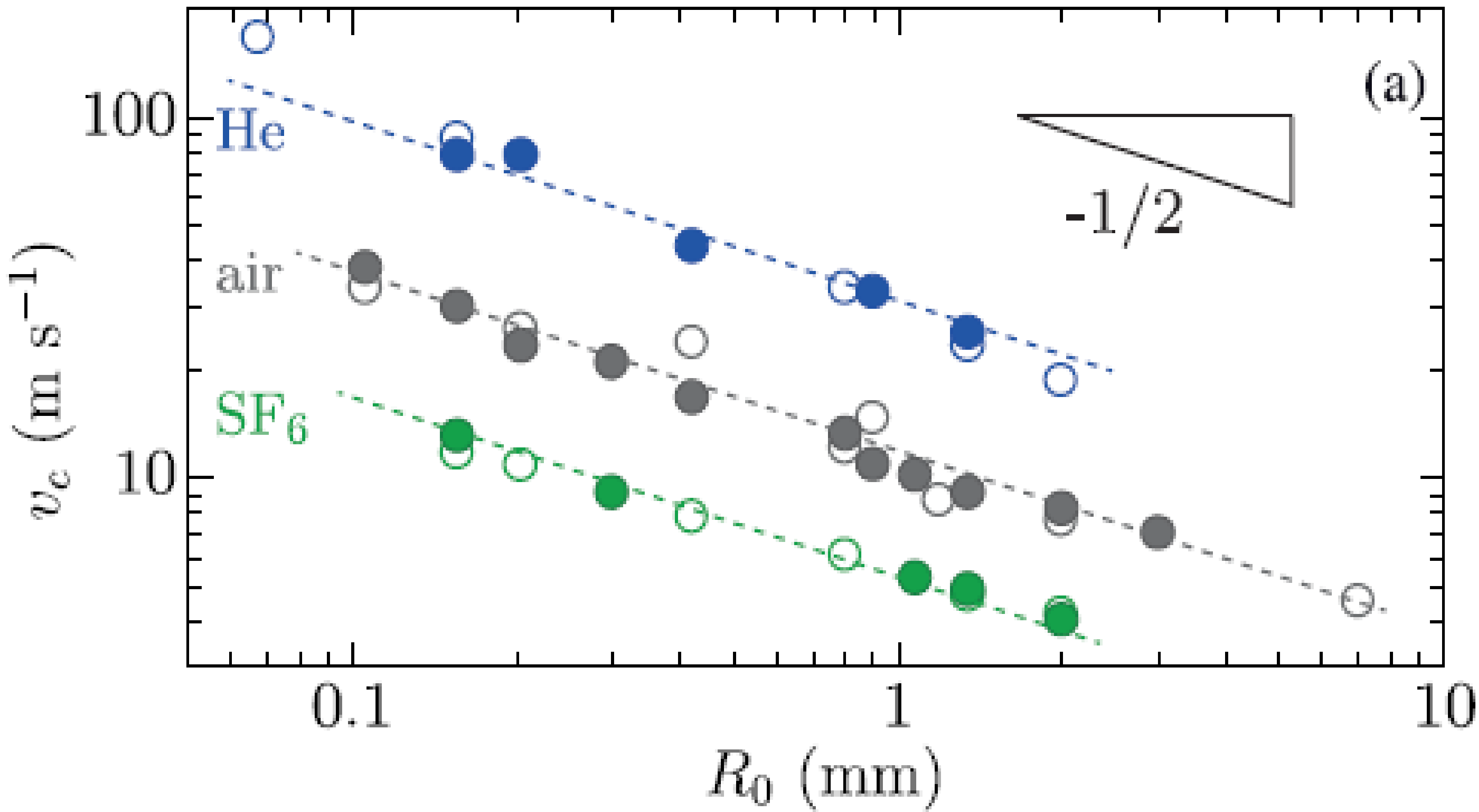
(c) $v_g < v_c$



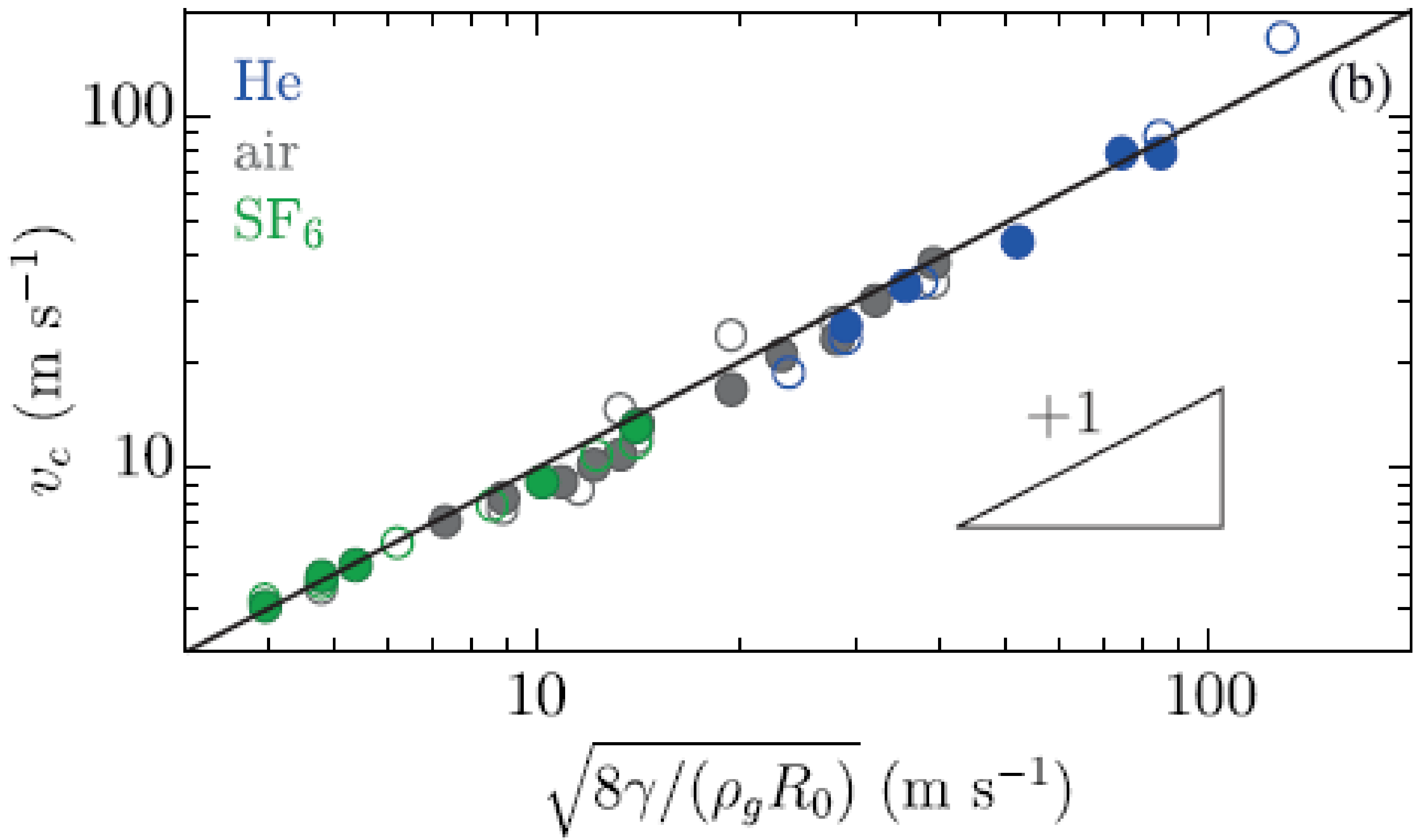
(d) $v_g > v_c$



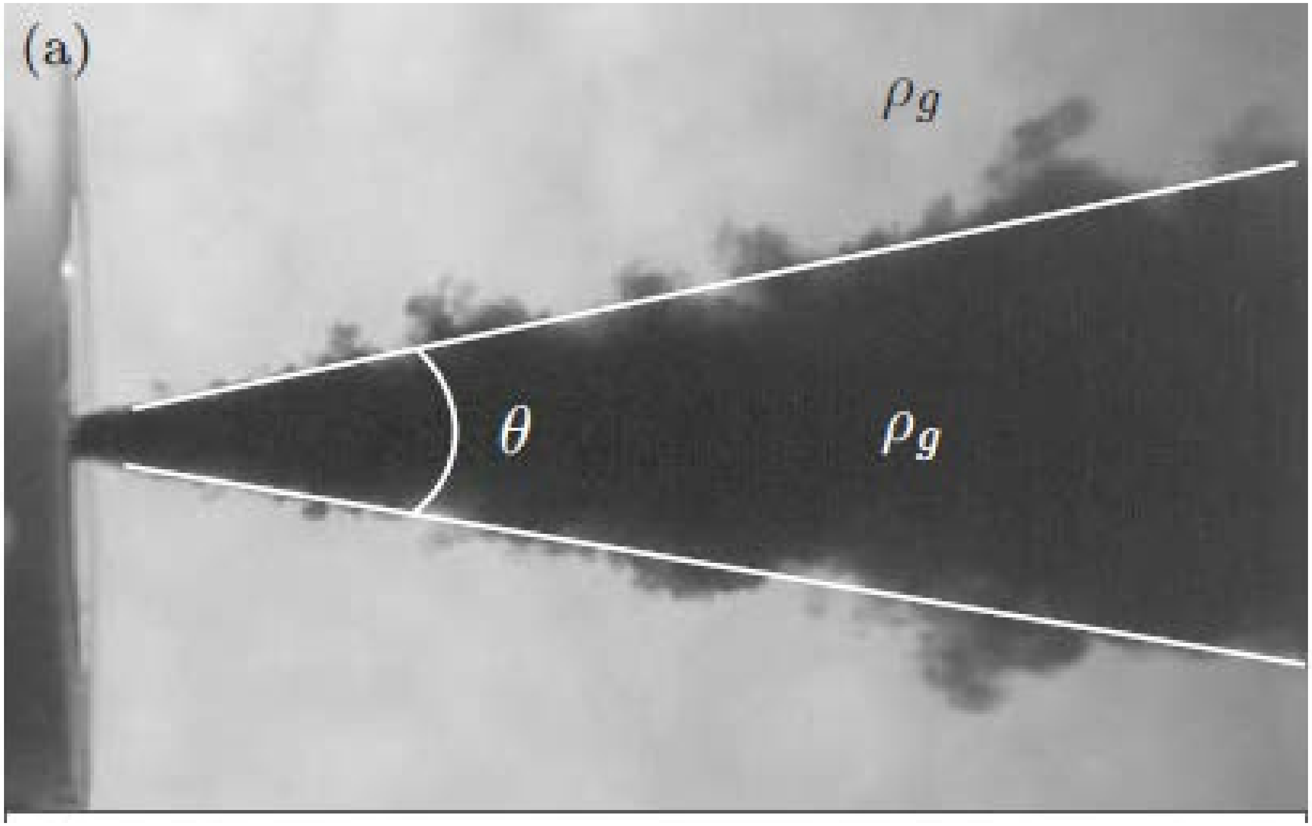
Critical speed v_c for bubble formation as a function of nozzle radius R_0 (nozzle close to the film)



Universal curve for critical speed v_c for different gases and nozzle radius R_0 (nozzle close to the film)

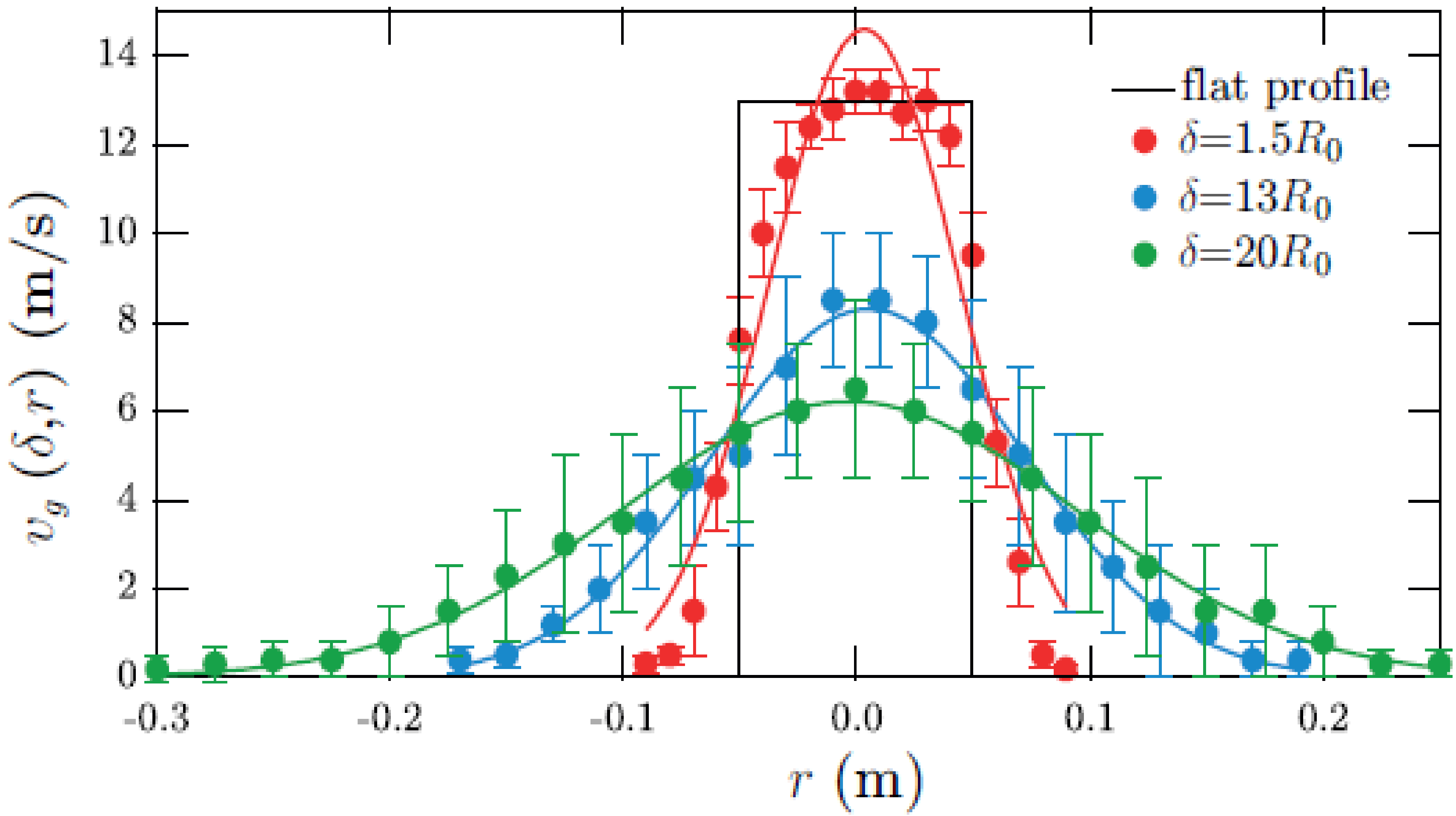


What happens when the nozzle is at a distance from the film ?

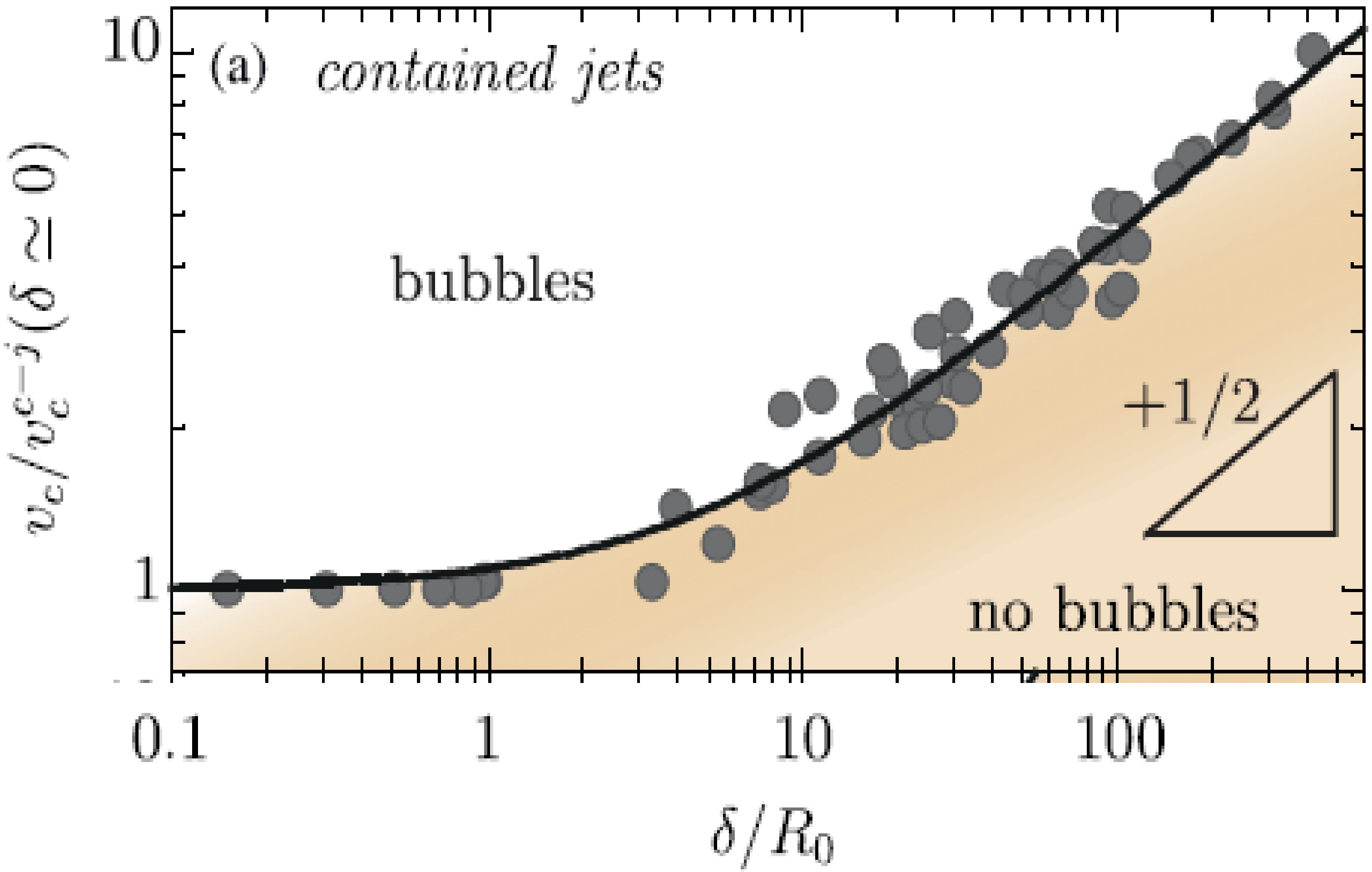


$$\theta = 23.6° \quad R(x) = R_0 + \frac{x}{5}$$

Velocity profile and critical velocity of air when the nozzle is at a distance from the film ?



Critical velocity $V_c = \sqrt{\frac{8T}{R_0 \rho}\left(1 + \frac{\delta}{5R_0}\right)}$

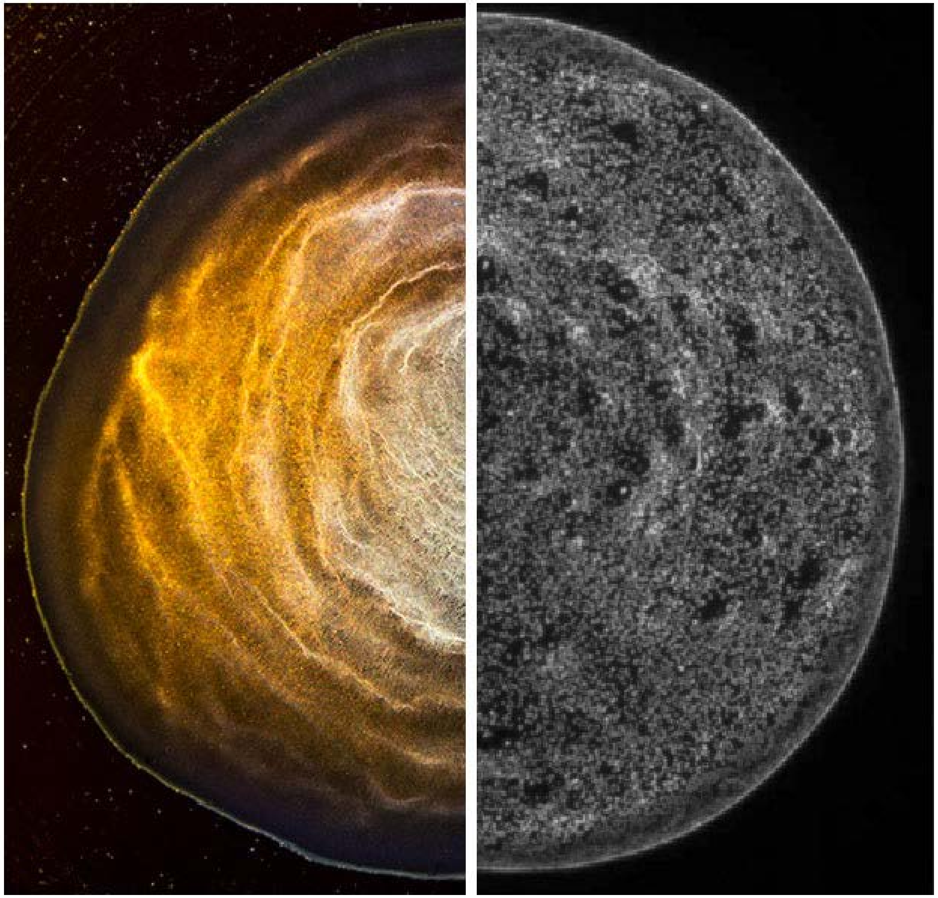


2. Whiskey

Controlled Uniform Coating from the Interplay of Marangoni Flows and Surface-Adsorbed Macromolecules

Physical Review Letters 116, 124501 (2016)

Hyoungsoo Kim, François Boulogne, Eujin Um, Ian Jacobi, Ernie Button, and Howard A. Stone



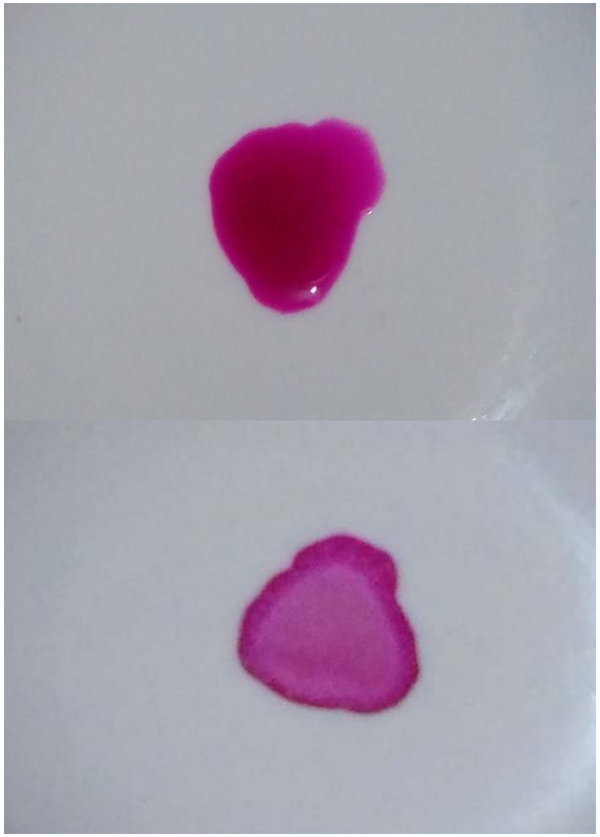
A dried mark of a whisky droplet (Macallan, UK) on a normal glass and a dried deposit pattern of a Glenlivet whisky (UK) with fluorescent polystyrene particles.

What is so special about the whisky droplet mark?

Normally one would tend to think that as the liquid matter in the drop evaporates, the residues left over would be distributed over the stain more or less uniformly.

But this is not what happens with a single liquid solution, for example when a coffee drop or a soup drop dries.

Let us look at what happens when a drop of coffee or colour solution in water dries up



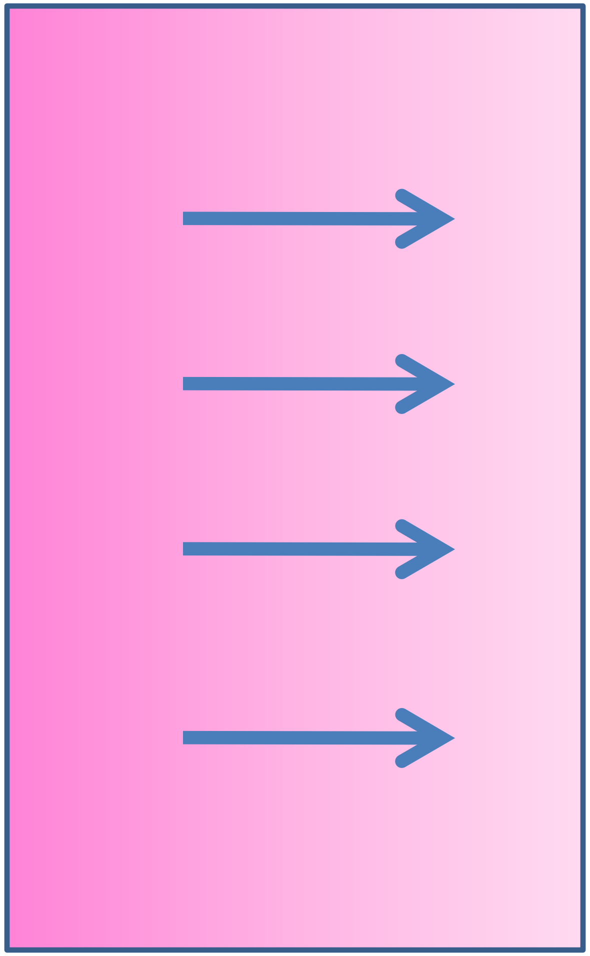
Understanding coffee-ring effect

Ficks law for particle diffusion

Thermal diffusion

Electrostatics

Particle diffusion



Fick's law of Diffusion

$$\vec{j}(\vec{r},t) = -D\vec{\nabla}\rho(\vec{r},t)$$

Continuity equation

$$\vec{\nabla}\cdot\vec{j}(\vec{r},t) + \frac{\partial\rho(\vec{r},t)}{\partial t} = 0$$

Steady state $\nabla^2\rho(\vec{r}) = 0$

Heat diffusion

Heat current $$\vec{j}_Q(\vec{r},t) = -K\,\vec{\nabla}T(\vec{r},t)$$

Change in temperature

$$\vec{\nabla}\cdot\vec{j}_Q(\vec{r},t) + C\,\frac{\partial T(\vec{r},t)}{\partial t} = 0$$

Steady state $$\nabla^2 T(\vec{r}) = 0$$

Electrostatics

Boundary value problem in for electrostatic potential without any charges

$$\nabla^2 \phi(\vec{r}) = 0$$

Electric field $\vec{E}(\vec{r}) = -\vec{\nabla}\phi(\vec{r})$

Solution of Lapalce's equation near an edge

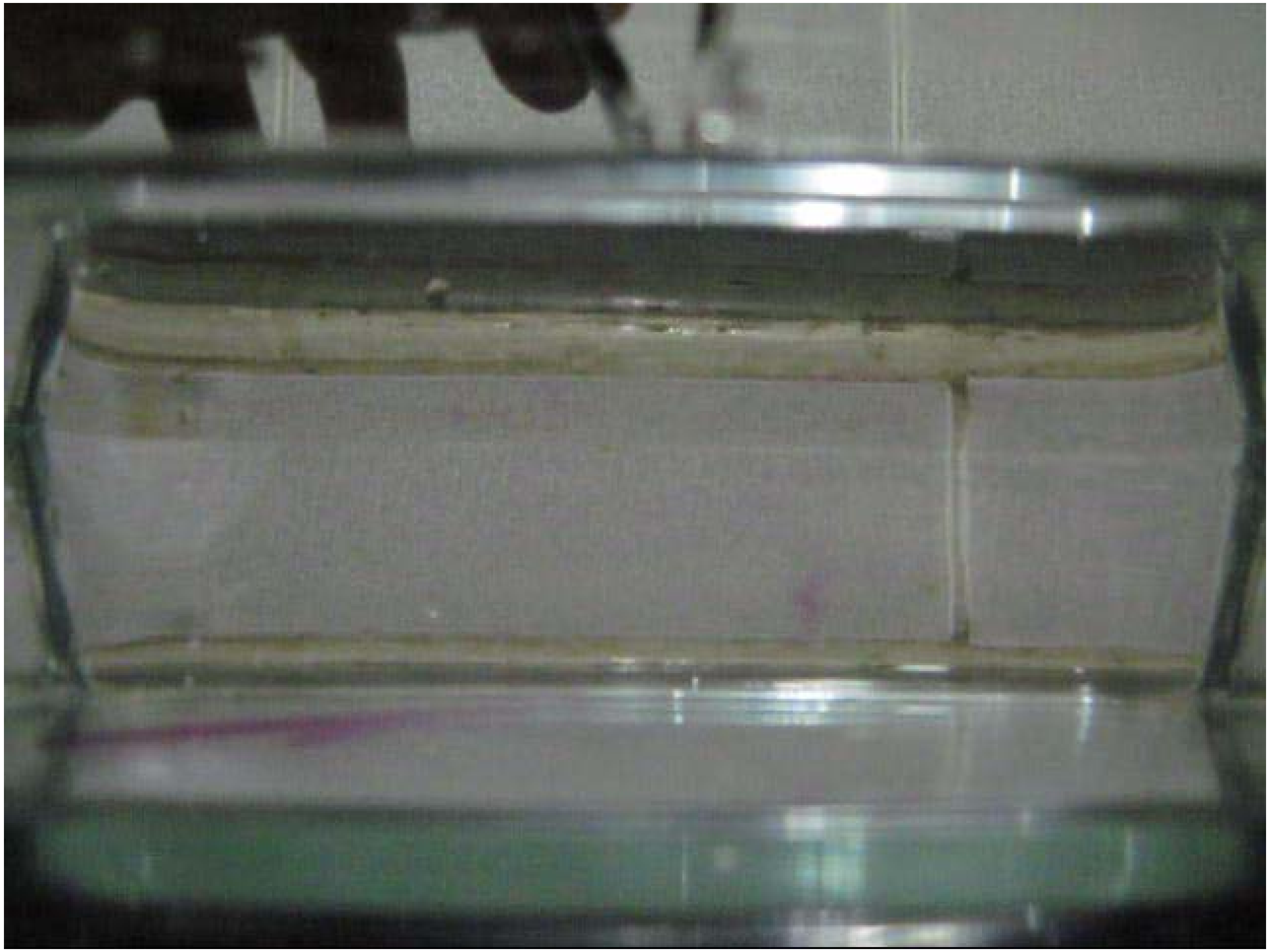
What does it describe?

i. Diffusion of particles near an edge

ii. Heat flowing out of an edge

iii. Electric field near a sharp corner

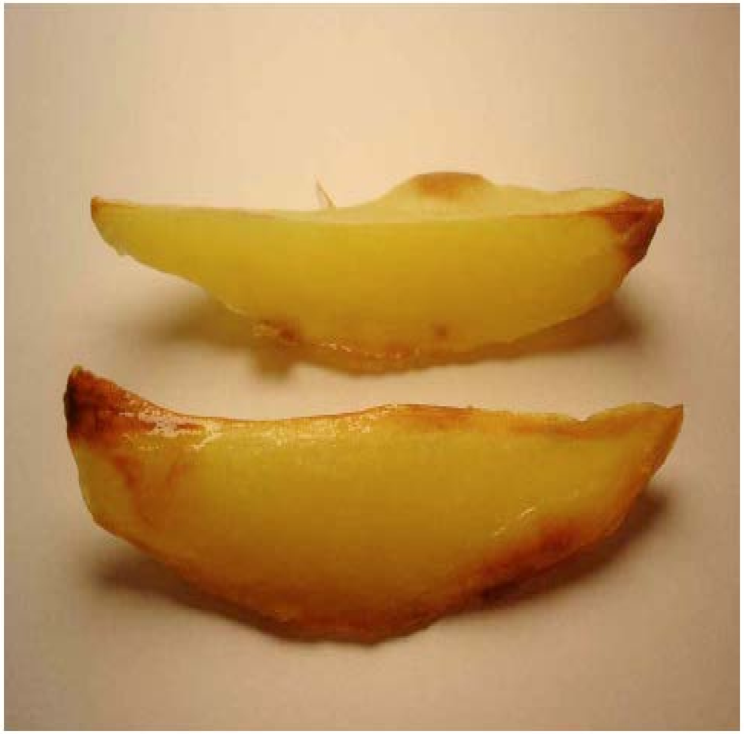
(Courtesy: Varun Harbola, Physics Department, Stanford Univ.)



(Courtesy: Varun Harbola, Physics Department, Stanford Univ.)

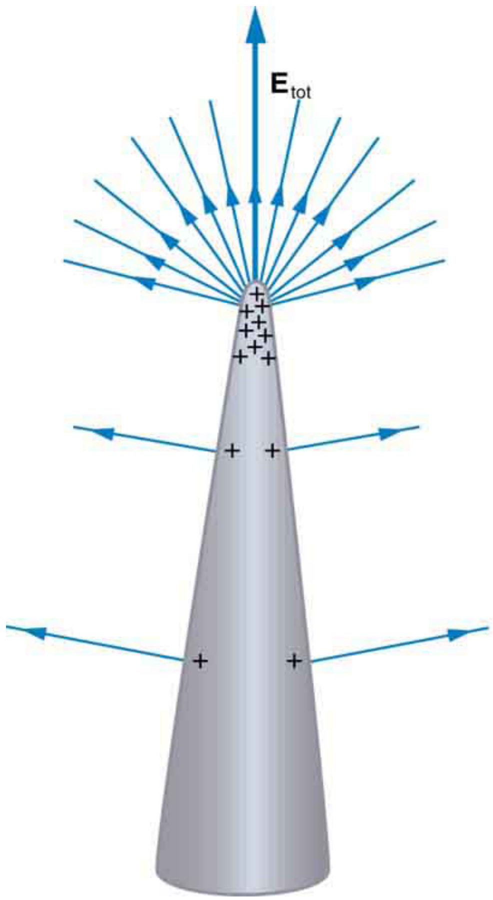
Related phenomena; potato wedges

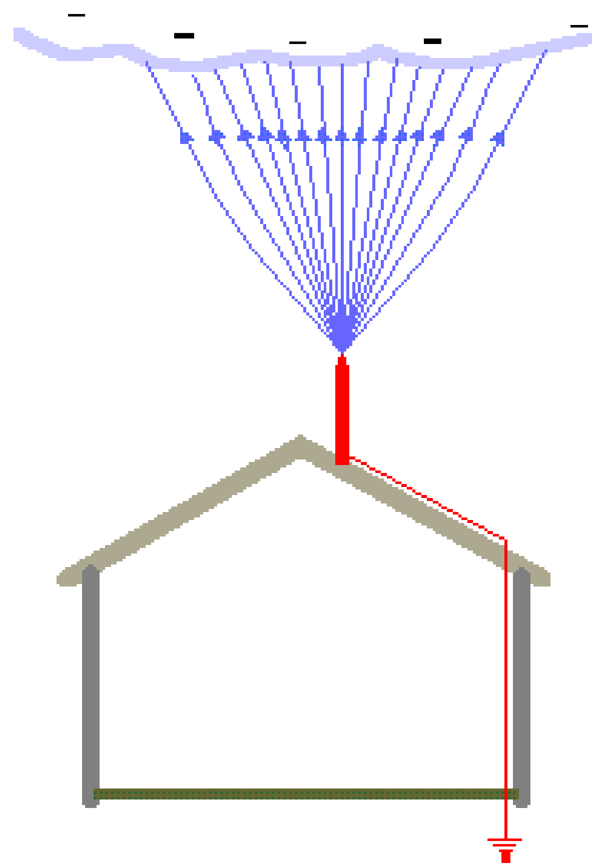
L. Bocquet, Am. J. Phys. 75, 148 (2007)



A small block of ice-cream melting

Electric field lines near a lightening rod

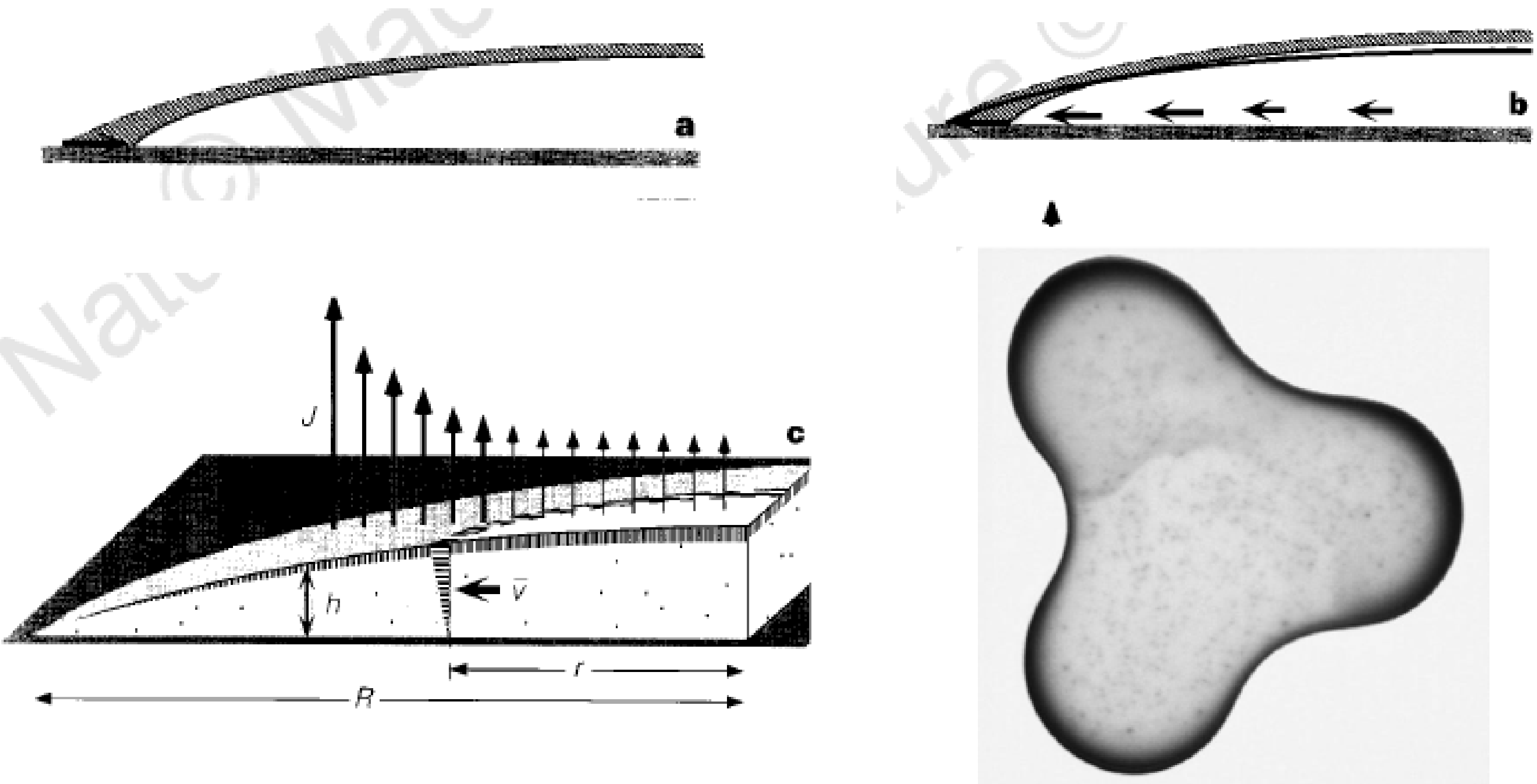


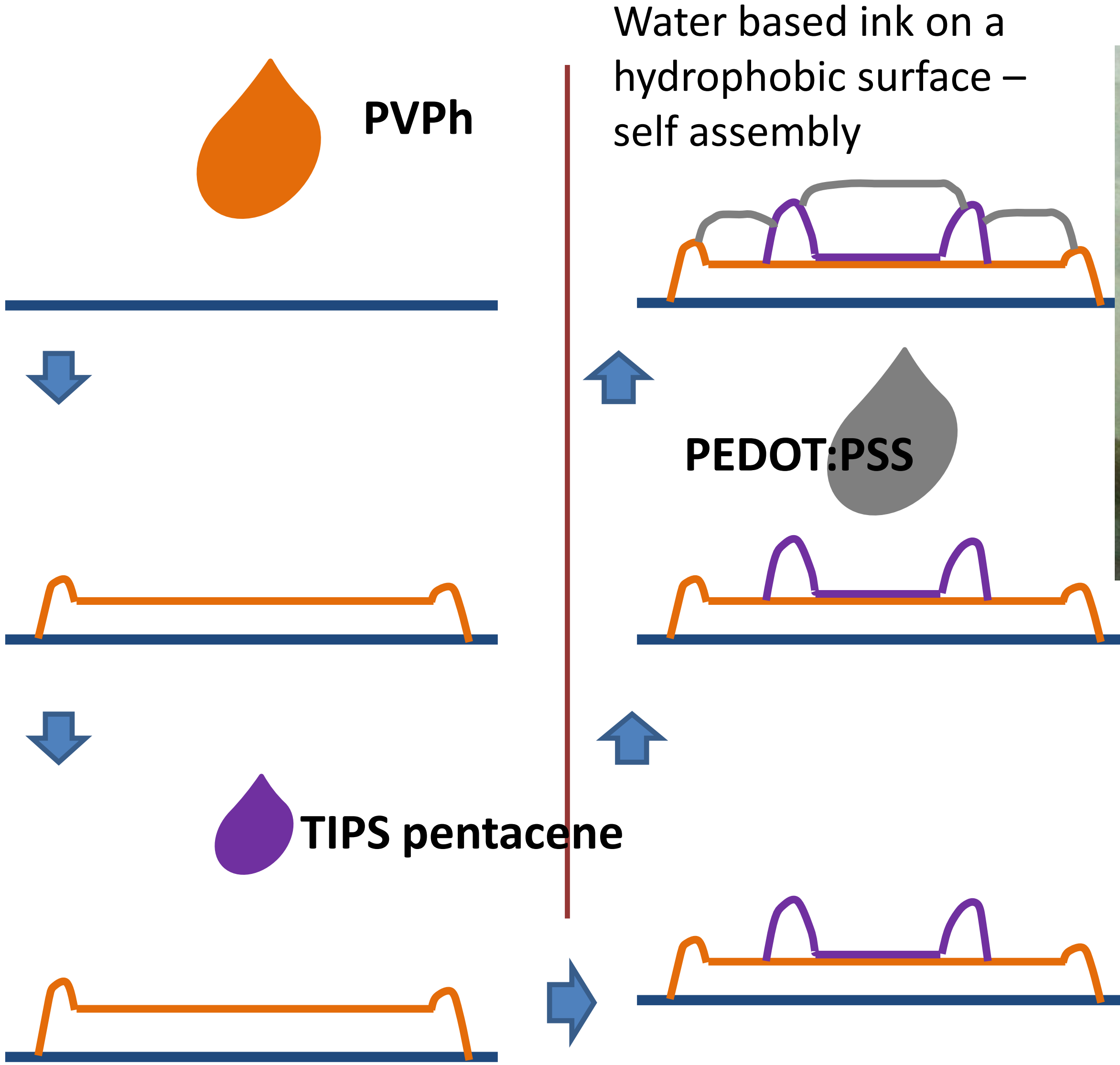


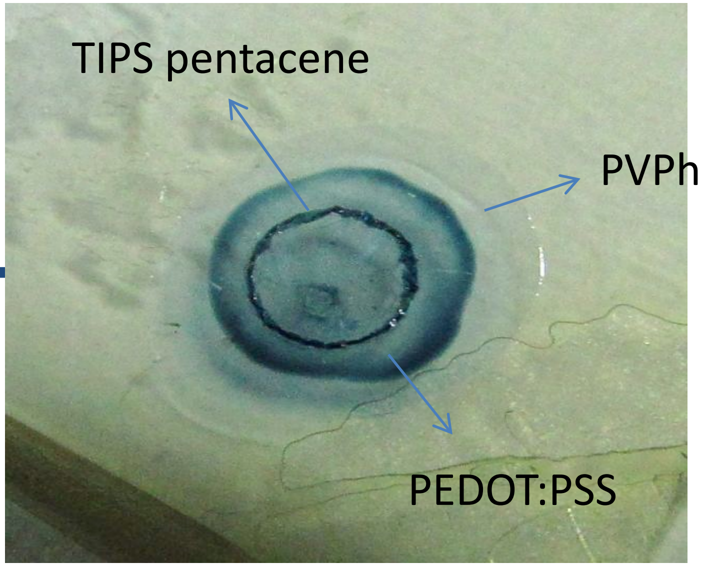
Courtesy: Images on the internet

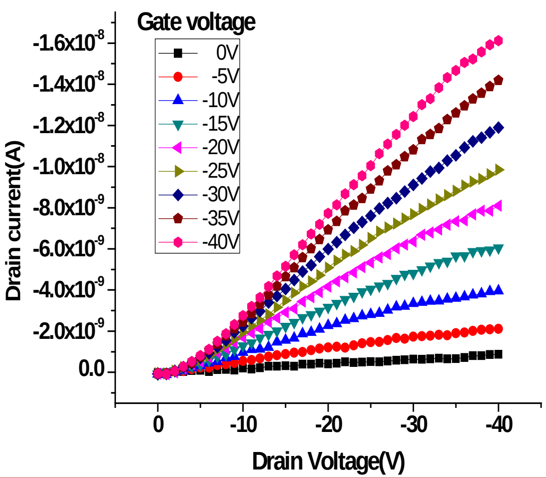
For a water drop also, the rate of evaporation will be largest near the edges of the drop

Deegan et al., Nature 389, 827 (1997)









*Saumen Mandal and Monica Katiyar, "**Fabrication of organic thin film transistor using single drops of organic or hybrid insulator, conductor and semiconductor materials**", filed for U.S. patent through Intellectual Venture (IN-837697-01-IN-REG)on April, 2013*

Inkjet-Printed Line Morphologies and Temperature Control of the Coffee Ring Effect

Dan Soltman* and Vivek Subramanian

Department of Electrical Engineering and Computer Science, University of California, Berkeley, California 94720

Received August 30, 2007. In Final Form: October 17, 2007

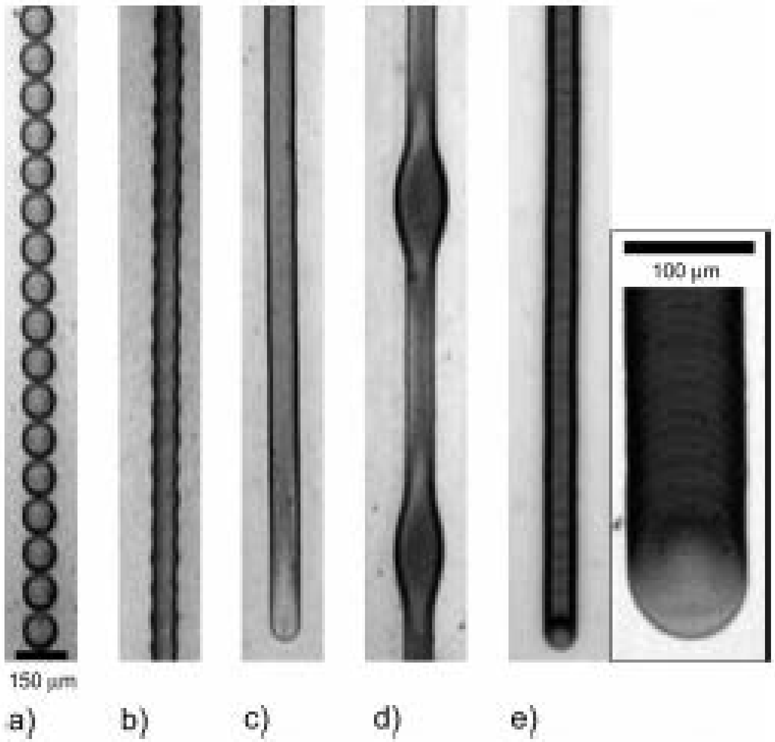


Figure 2. Examples of principal printed line behaviors: (a) individual drops, (b) scalloped, (c) uniform, (d) bulging, and (e) stacked coins. Drop spacing decreases from left to right.

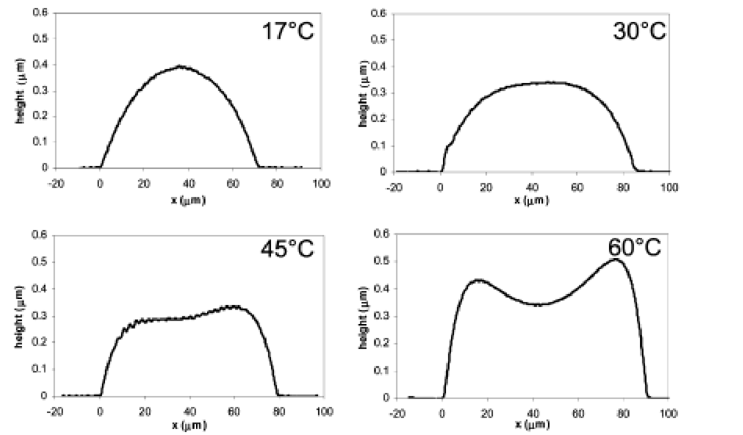


Figure 5. Cross-sectional profile of uniform lines printed at the noted temperature using a mechanical stylus profiler. (The delay and spacing are adjusted to be appropriate for each temperature.)

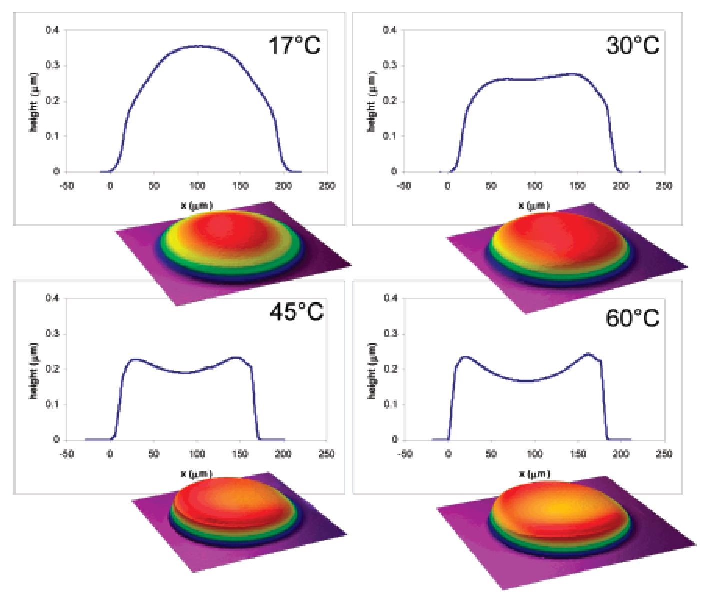


Figure 6. Cross section and 3D projection from an optical profilometer of single drops printed at the noted temperatures.

How can coffee rings be controlled?

Marangoni Effect Reverses Coffee-Ring Depositions

Langmuir 21, 2971 (2005) and J. Chem. Phys. B 110, 7090 (2006)

Hua Hu and Ronald G. Larson

3. Wine

Courtesy: Images on the internet

Understanding Marangoni effect

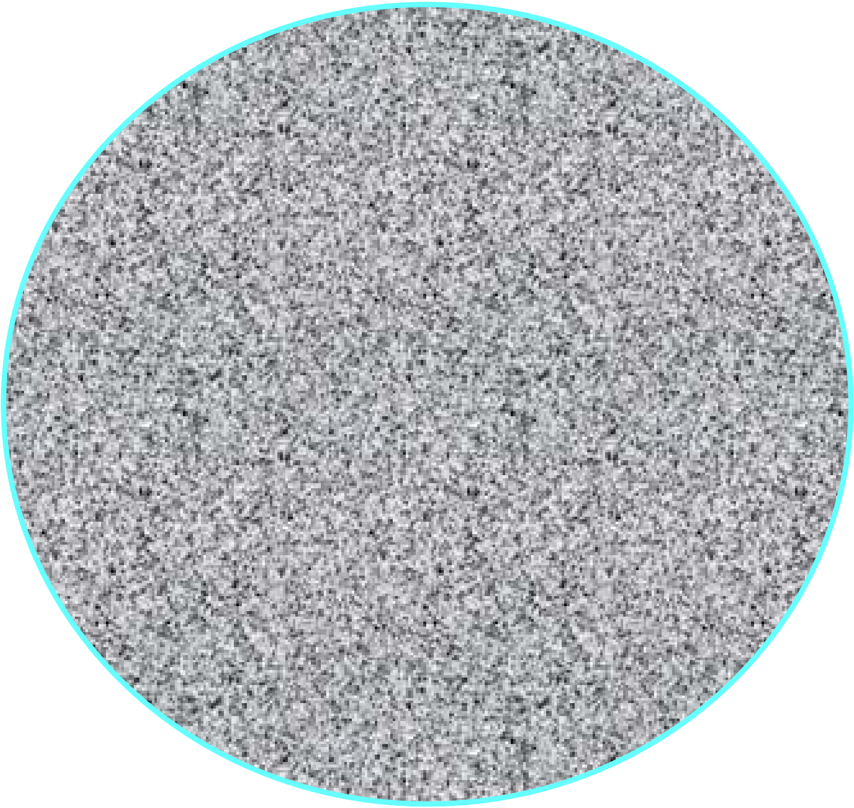
i. Surface Tension gradient causes liquid to flow from the surface of lower surface tension to that of higher surface tension;

ii. This happen because the force on a line between two regions is higher because of the liquid of higher surface tension; or equivalently

iii. Larger the area of liquid of lower surface tension, lower the energy of the system

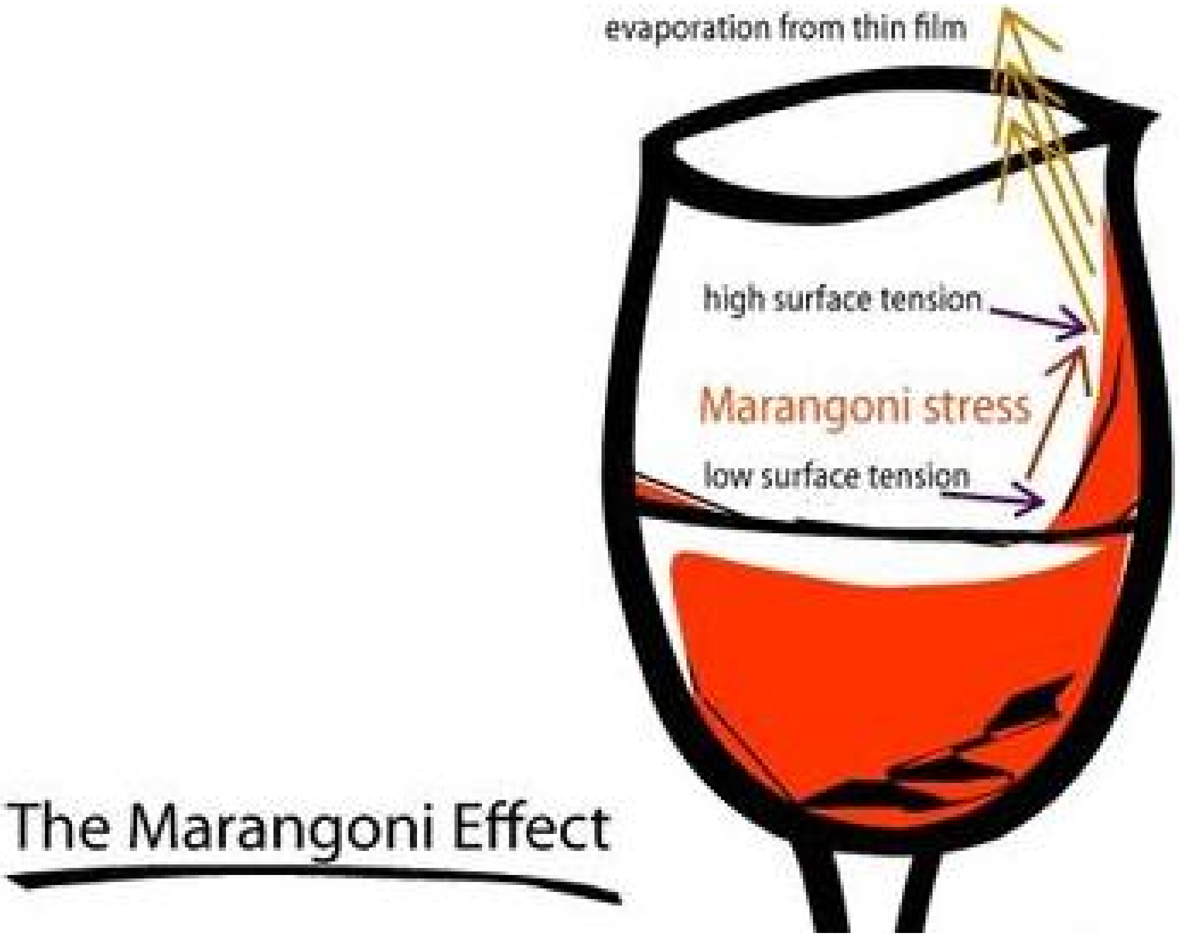
Watching Marangoni effect

Boat driven by
a soap solution



Black pepper on
water surface

What happens in a wine glass?



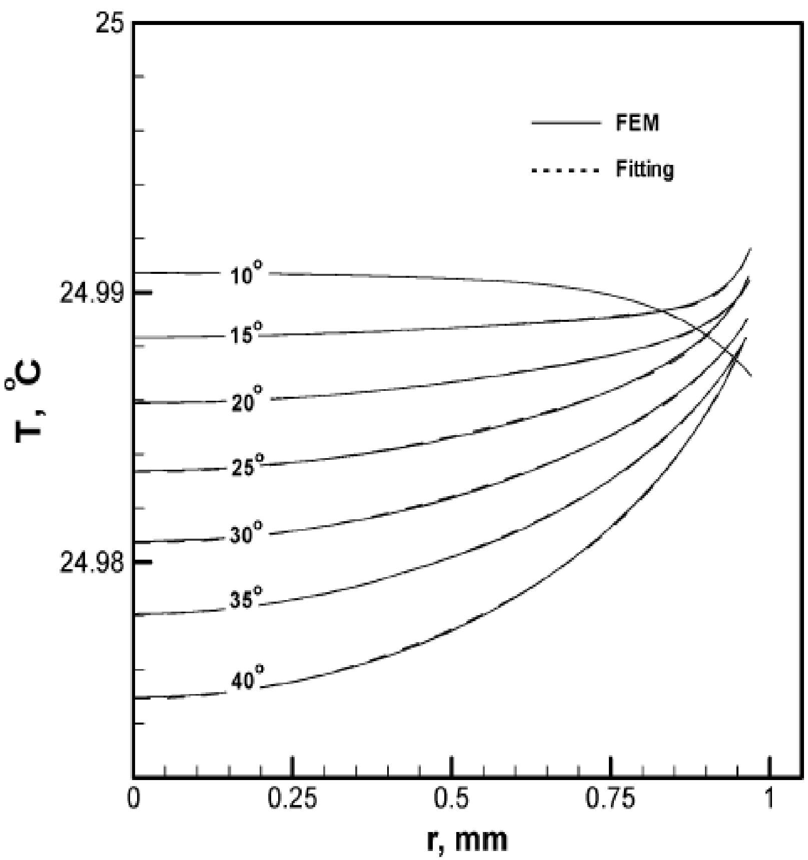
How else can the surface tension of a liquid change?

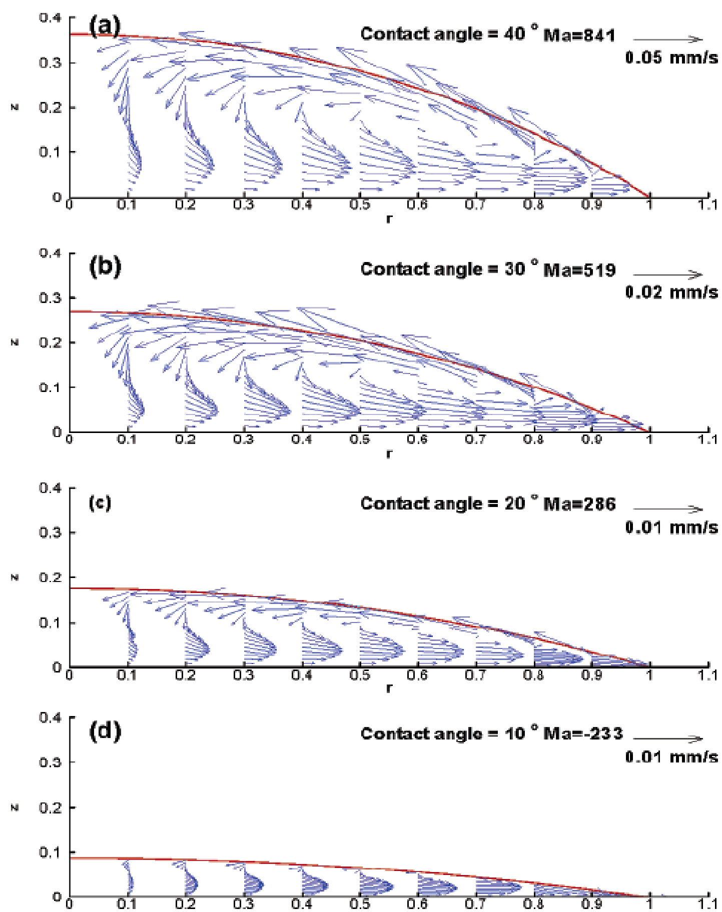
i. Surface tension is lower at higher temperatures

ii. Surface tension becomes smaller when a surfactant is mixed in a liquid

Back to drying droplets (R ~ 100μm); Marangoni effect reverses coffee-ring effect

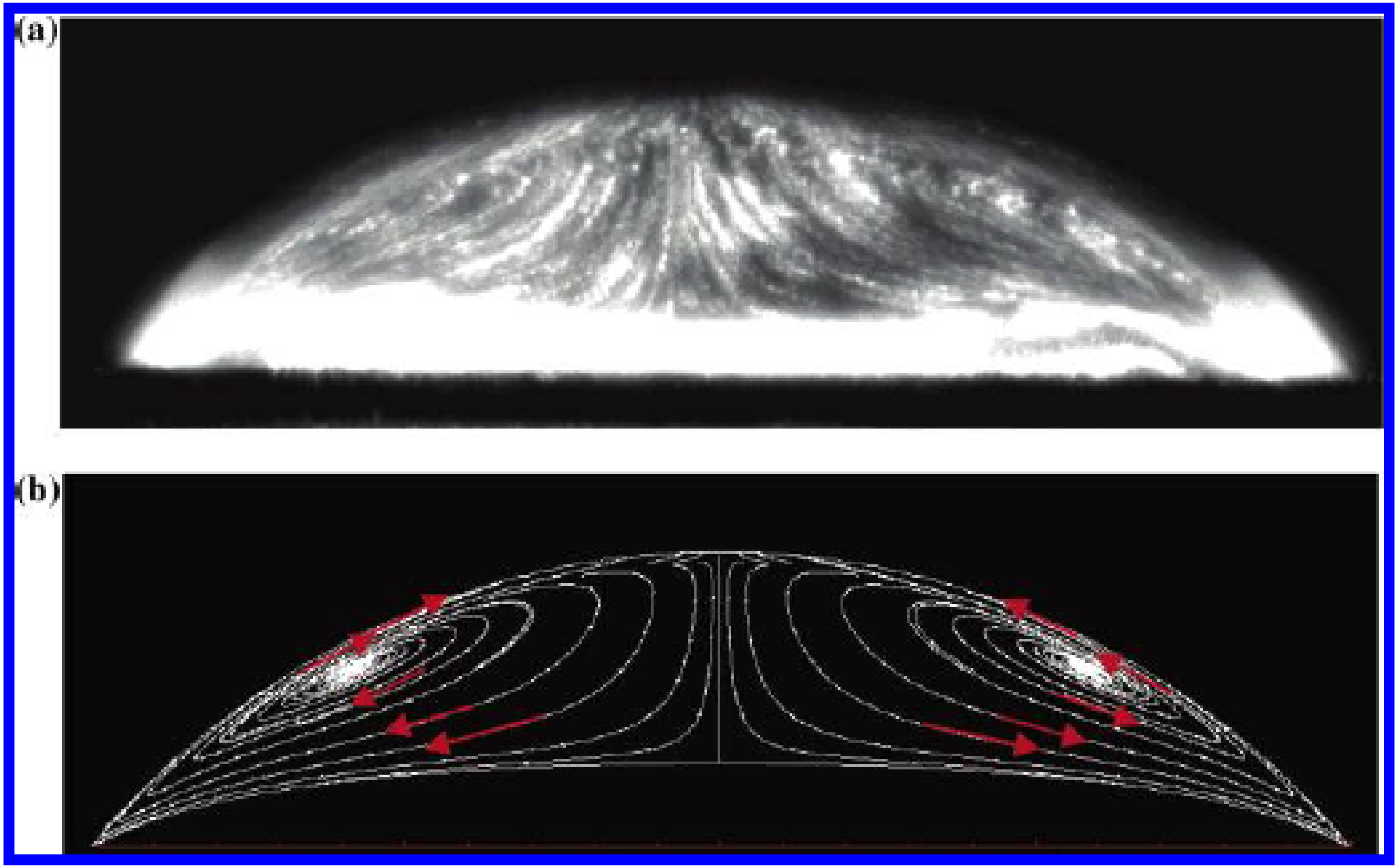
Hu & Larson, Langmuir **21**, 3971 (2005);
ibid, J. Chem. Phys. B **110**, 7090 (2006)





Flow field in a drying octane droplet (a) experimental image and (b) predicted at high Marangoni number

(Hu and Larson, J. Chem. Phys. B 110, 7090 (2006)



What happens in a water droplet?

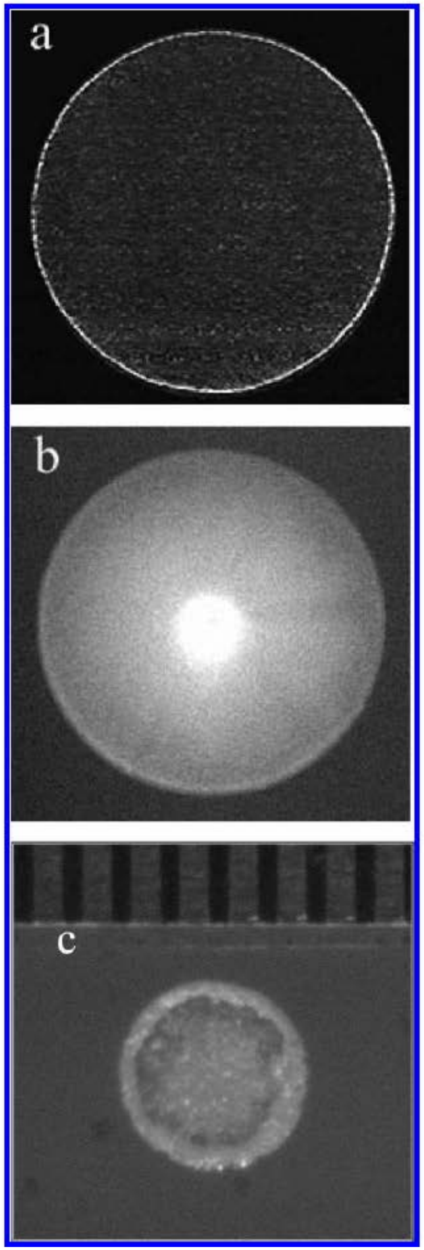
Contamination in water is suspected to reduce the Marangoni effect significantly

Hu & Larson, Langmuir **21**, 3971 (2005);
ibid, J. Chem. Phys. B **110**, 7090 (2006)

Ring deposition pattern of fluorescent ploystyrene particles in a water droplet

Deposition pattern of fluorescent PMMA particles in an octane droplet

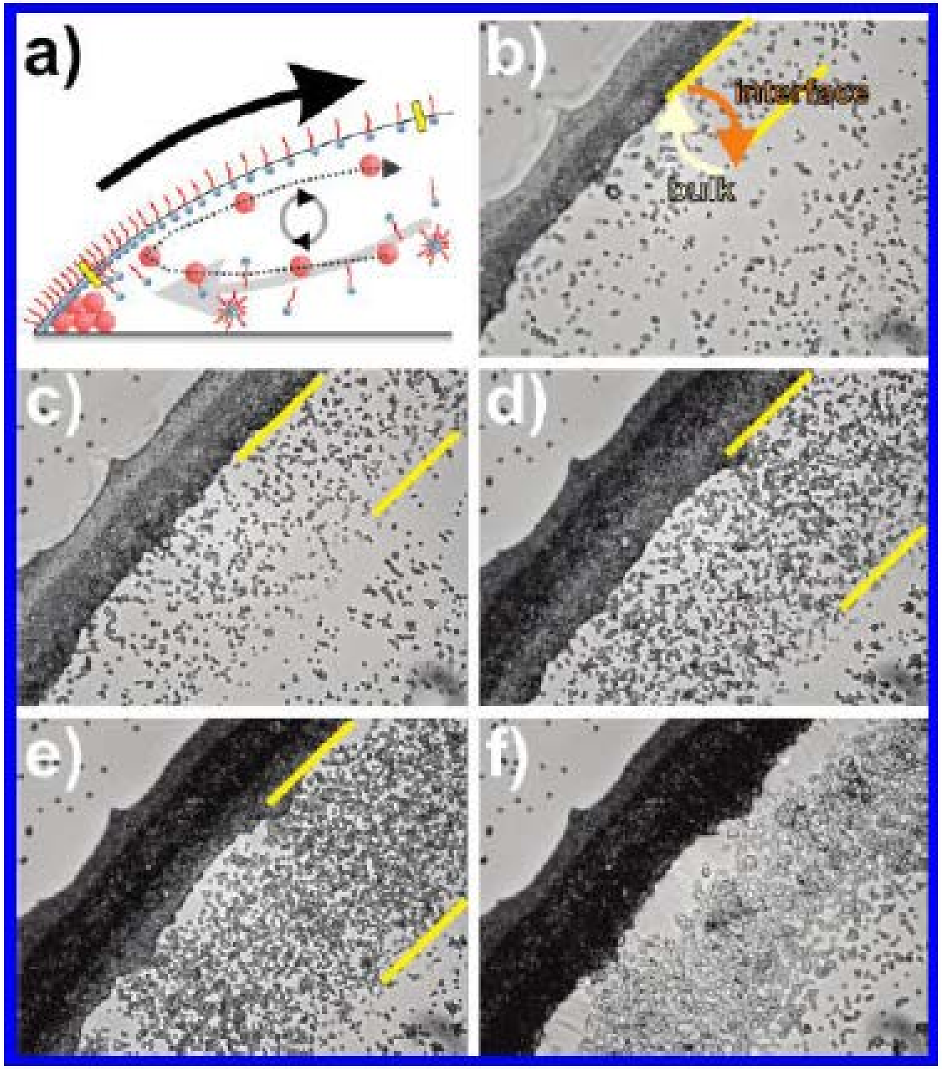
Deposition pattern of mica particles in an octane droplet



Hu and Larson, J. Chem. Phys. B 110, 7090 (2006)

Surfactant induced Marangoni effect and reversal of coffee-ring effect

Still, Yunker and Yodh, Langmuir, 28, 4984 (2012)



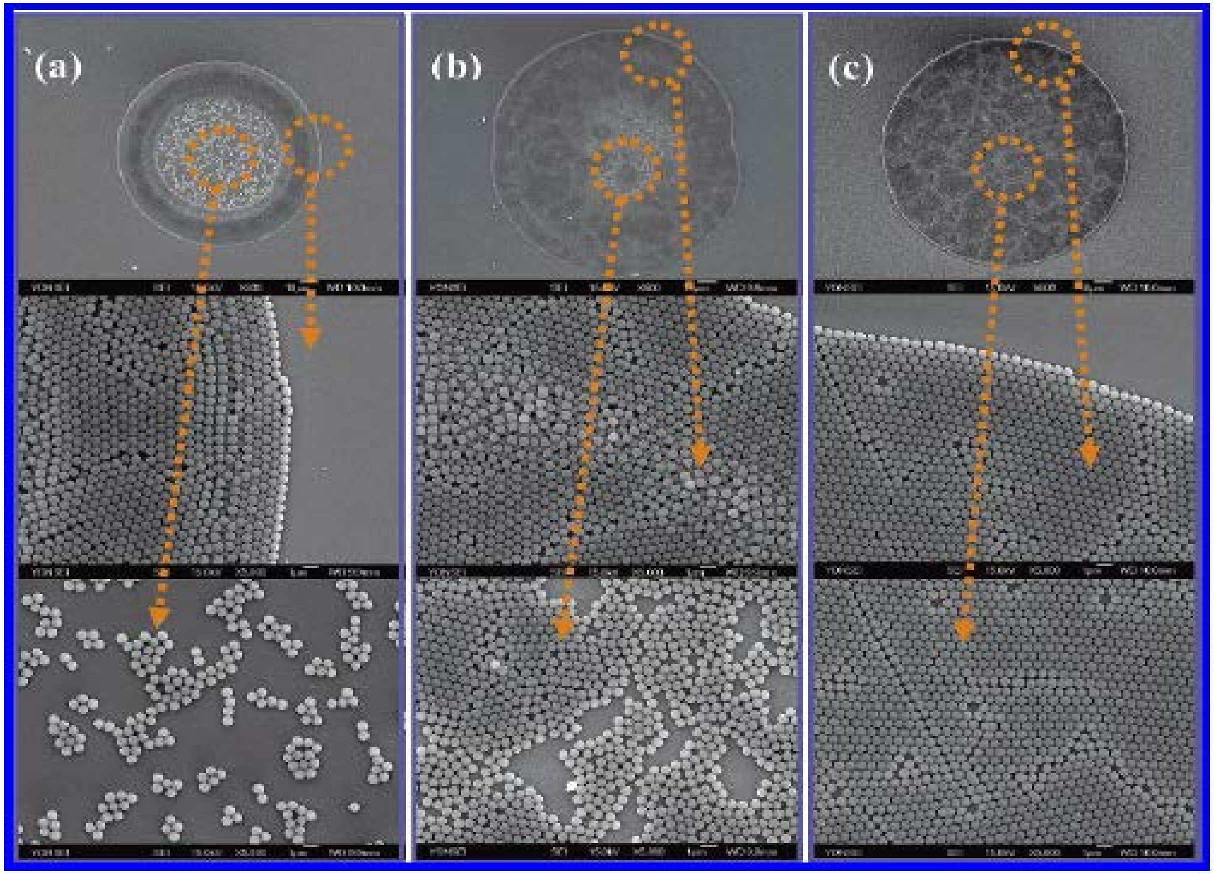
Achieving uniform deposition using binary-mixture as solvent ($R \sim 50\text{-}70\ \mu m$)

Park and Moon, Langmuir 22, 3506 (2006)

Talbot et al., ACS Appl. Mater. Interfaces 7, 3782 (2015)

Park and Moon, Langmuir 22, 3506 (2006)

Silica microspheres in a single ink-jet droplet made by ink-jet printing



Water-based ink

Water+DEG based ink

Water+FA based ink

Talbot et al., ACS Appl. Mater. Interfaces 7, 3782 (2015)

Droplets (R ~ 100μm) containing polystyrene spheres

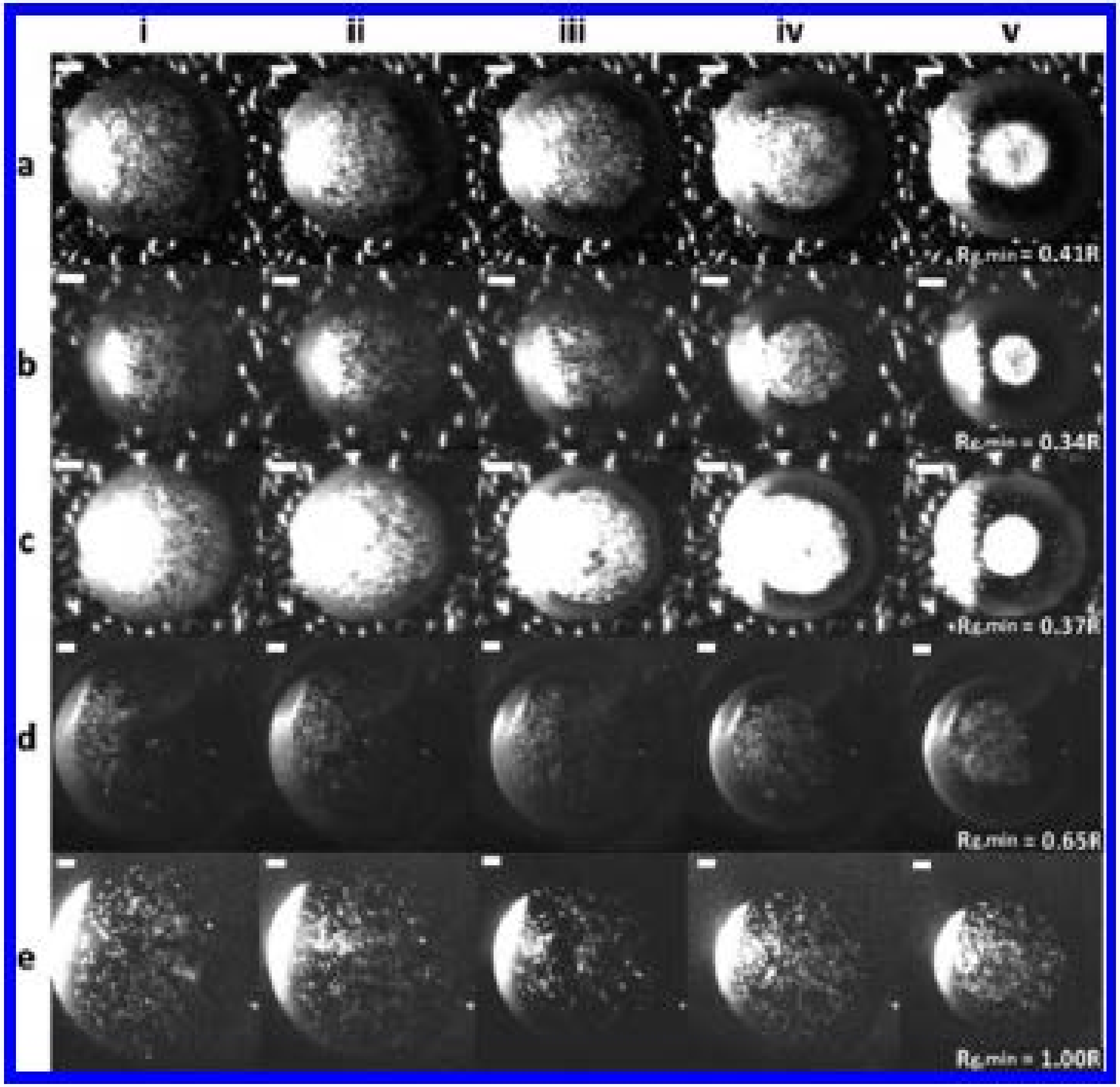
10% ethanol/water

30% ethanol/water

50% ethanol/water

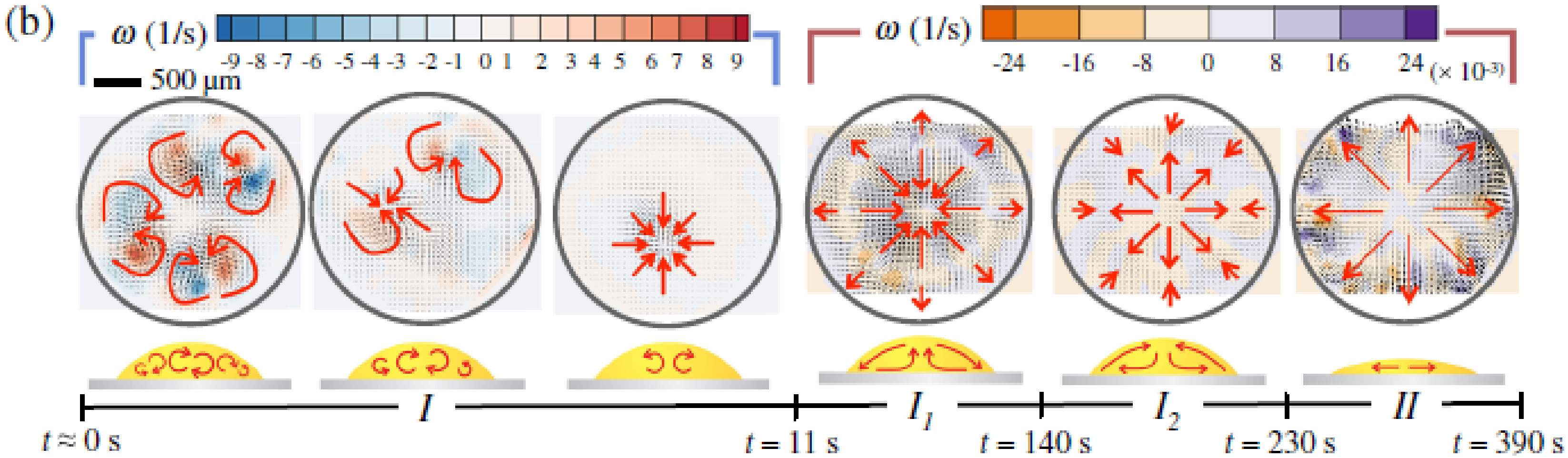
70% ethanol/water

90% ethanol/water



Back to whiskey droplets (R ~ 1-5mm)?

SI movie 1



Does ethanol also reverse coffee-ring effect in larger drops ?

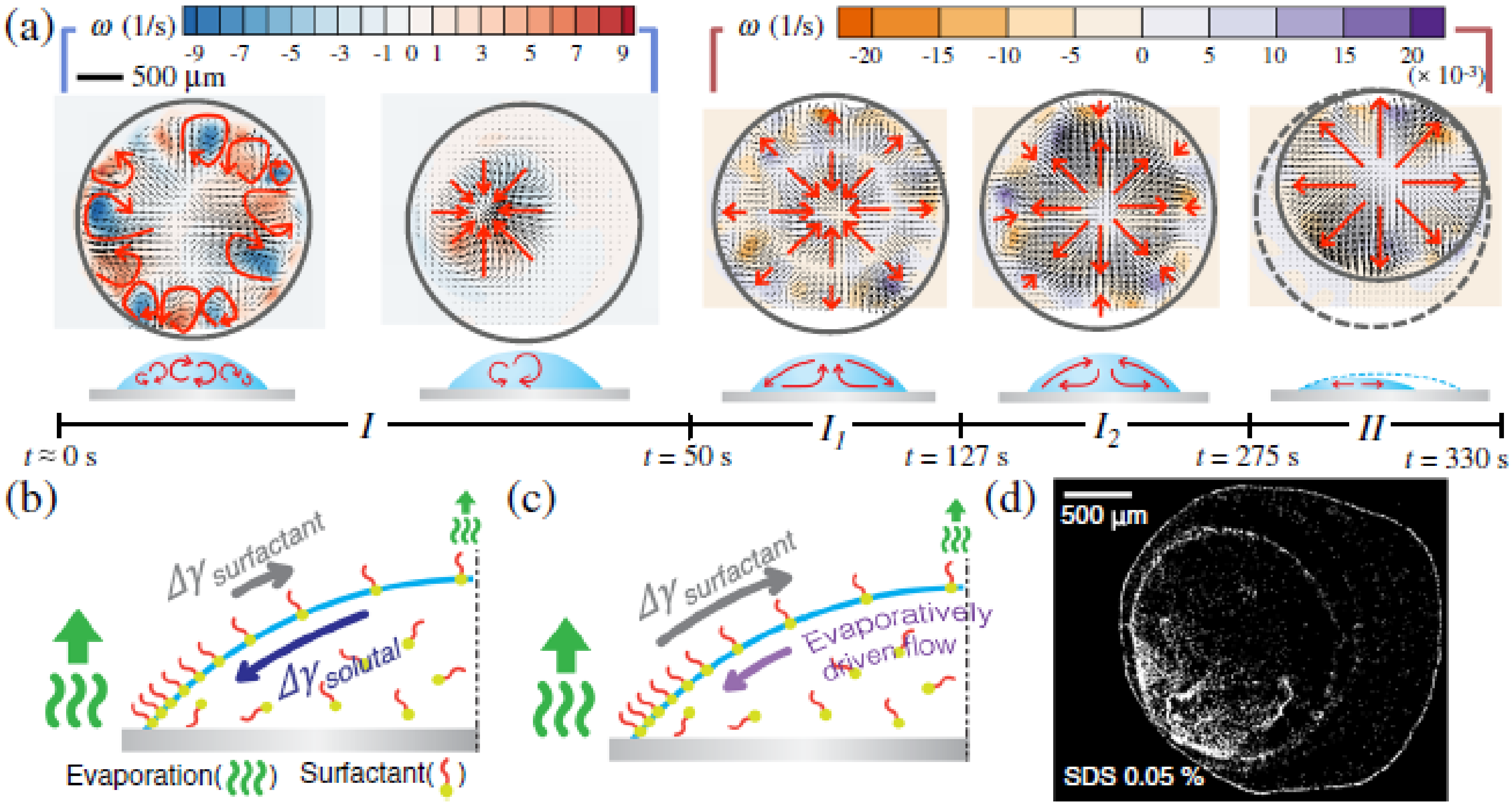
SI movie 2

Surfactant in whisky reversing coffee-ring effect by creating surfactant-driven Marangoni effect

SI movie 3

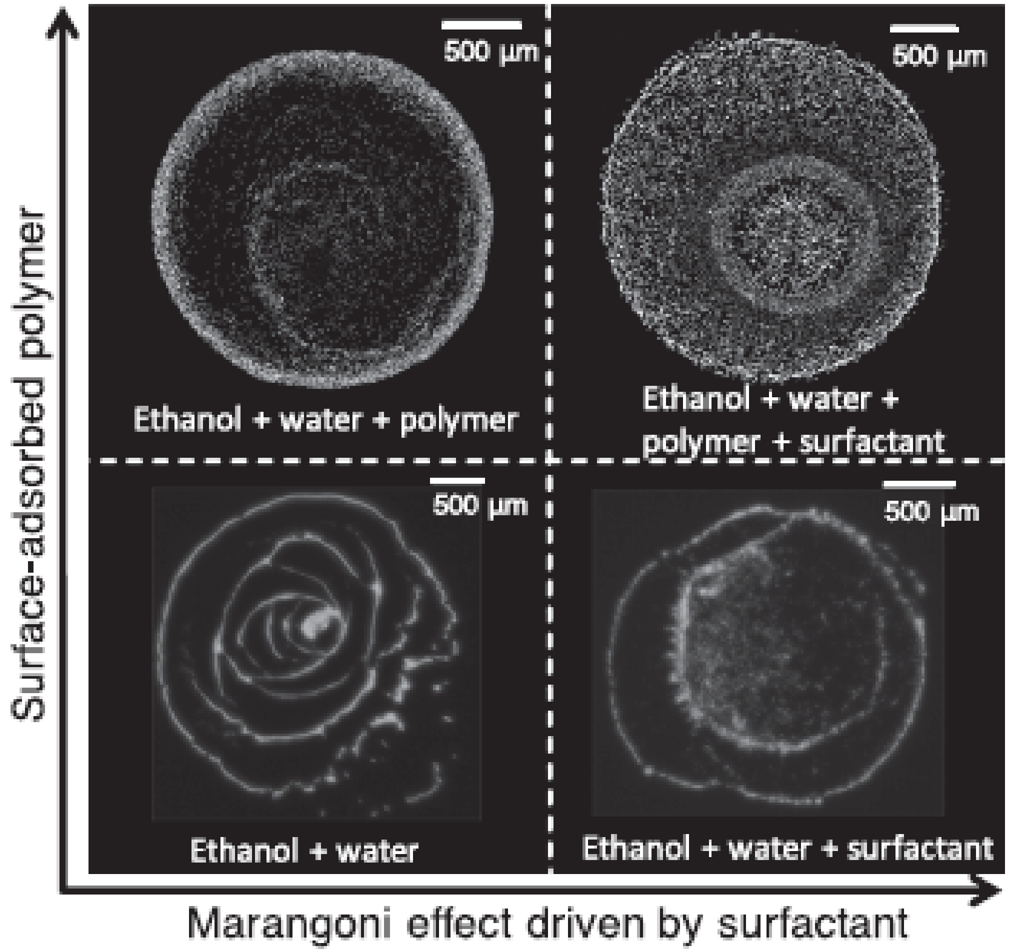
Checking the role of surfactant-driven Marangoni effect with sodium dodecyl sulfate (SDS) in ethanol-water mixture

SI movie 4

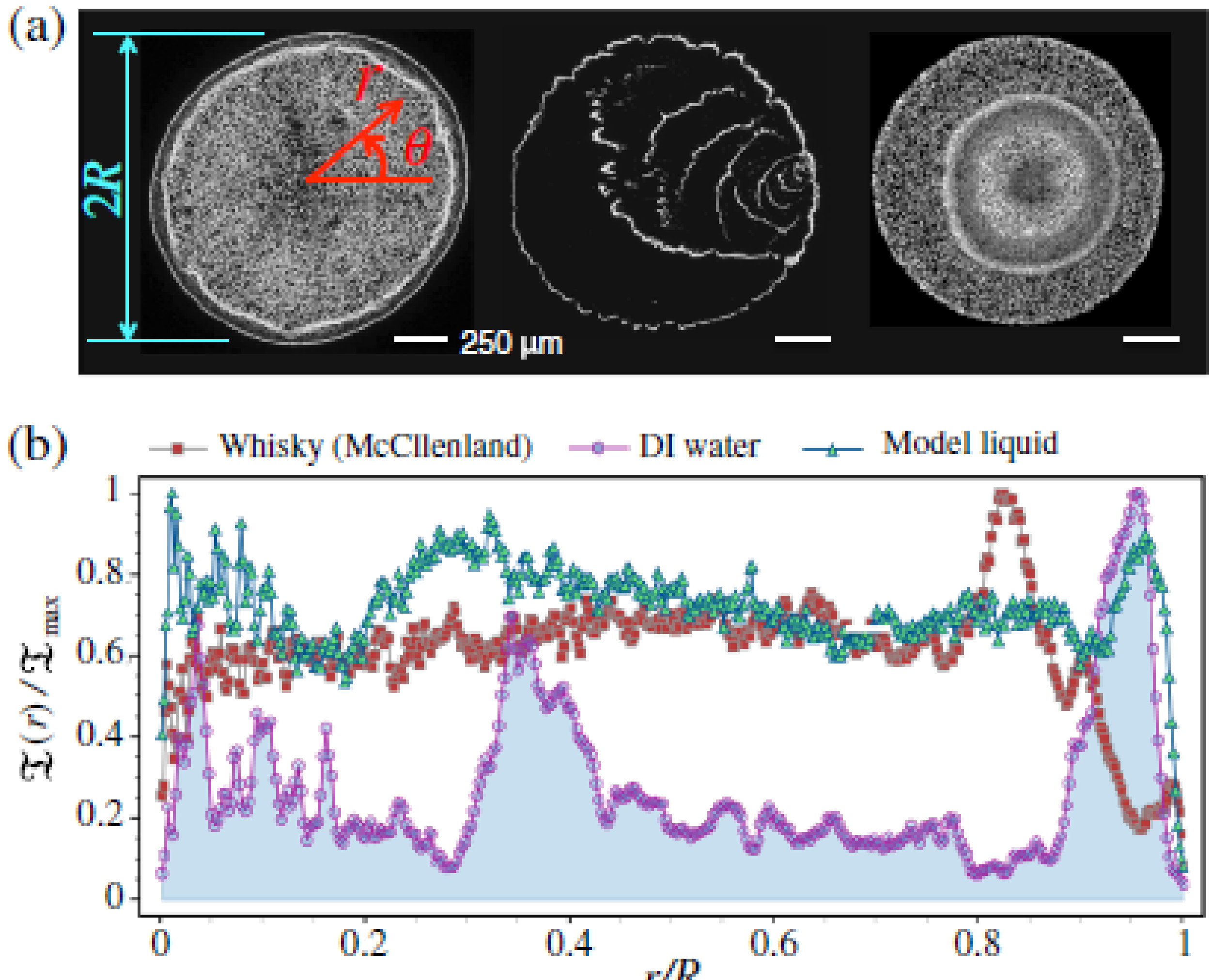

(a)
ω (1/s)
-9 -7 -5 -3 -1 0 1 3 5 7 9
500 μm
ω (1/s)
-20 -15 -10 -5 0 5 10 15 20
(× 10⁻³)
I
I1
I2
II
t ≈ 0 s
t = 50 s
t = 127 s
t = 275 s
t = 330 s
(b)
Δγ surfactant
Δγ solutal
Evaporation( )
Surfactant( )
(c)
Δγ surfactant
Evaporatively driven flow
(d)
500 μm
SDS 0.05 %

Drying of a droplet of model liquid-drop with polymer and sodium dodecyl sulfate (SDS) in ethanol-water mixture

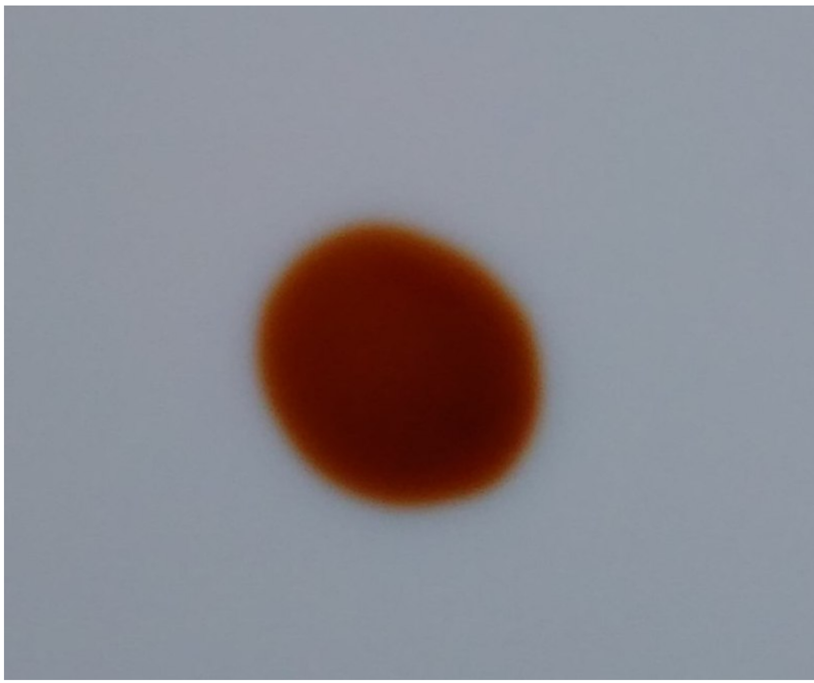
SI movie 5

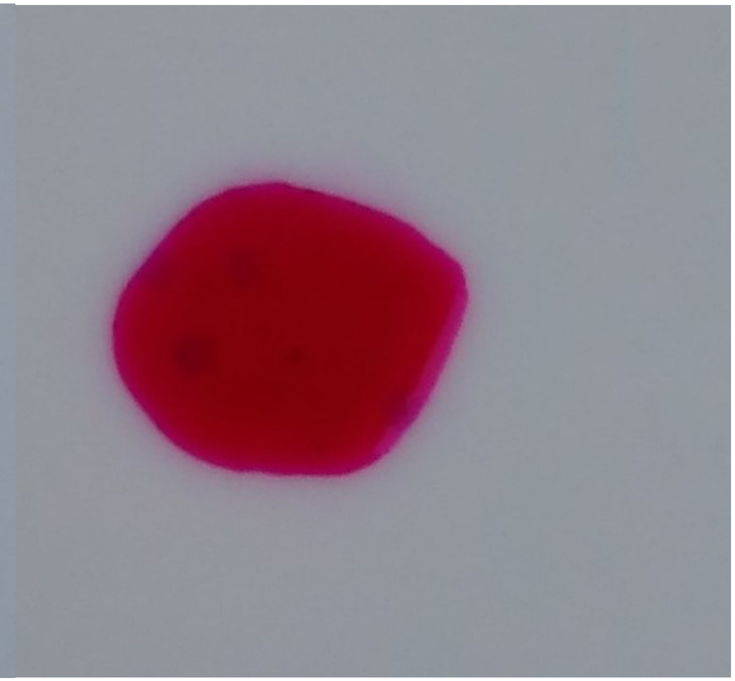


Deposition pattern of whiskey, DI water and a model liquid

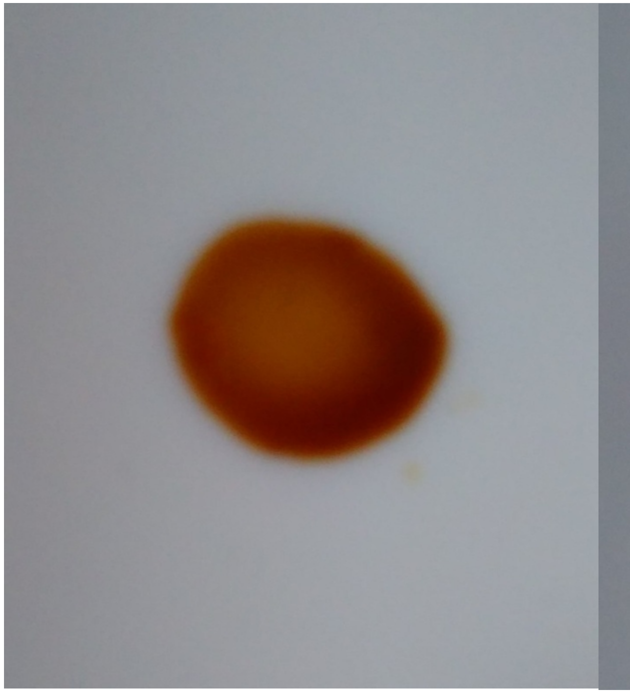
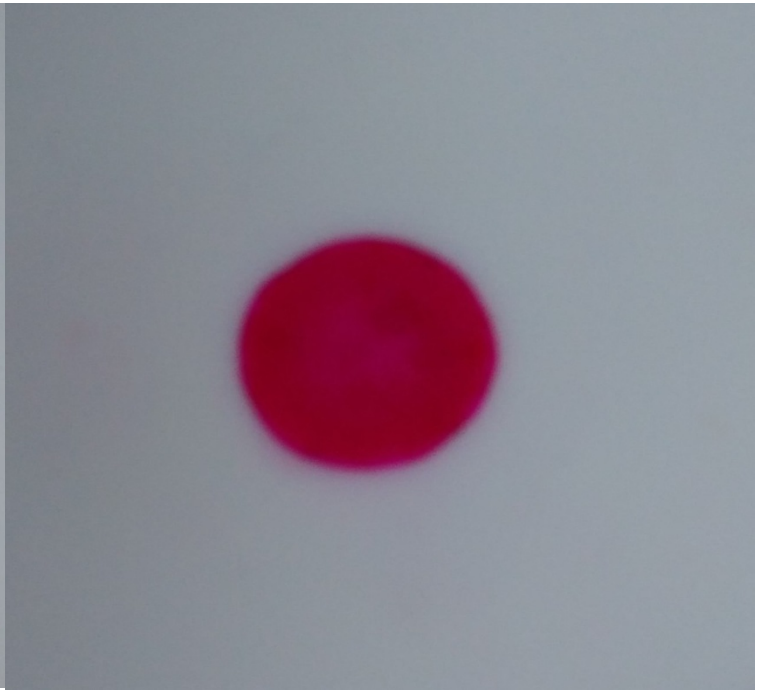


Experiments with sugar solution droplets





Very dilute sugar solution droplets

Concluding Remarks

Surface tension driven effects give rise to many interesting phenomena. We have discussed two of these , viz. the bubble formation and drying of droplets, and seen how the manipulating surface tension can give rise to interesting effects.

THANK YOU