Evaporation of colloids droplets containing PBS

A. Darras, N. Vandewalle, G. Lumay

GRASP, CESAM
Physics Department, University of Liège

March 2018

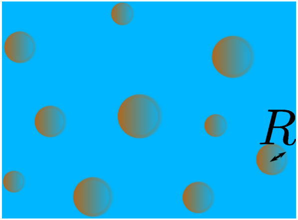
Table of contents

Table of contents

Colloids

Everyday life :

Particles suspension

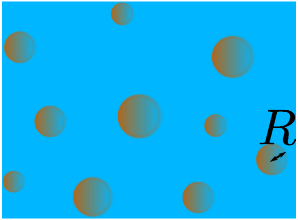


$k_B T \gg \rho g R^4$

Colloids

Everyday life :

Particles suspension

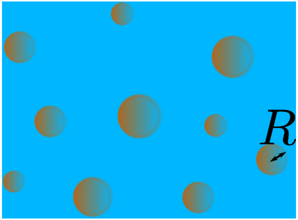


$$k_B T \gg \rho g R^4$$

Colloids

Everyday life :

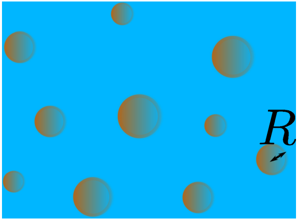
Particles suspension



$$k_B T \gg \rho g R^4$$

Colloids

Particles suspension

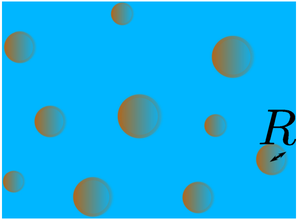


$$k_B T \gg \rho g R^4$$

Everyday life :

Colloids

Particles suspension

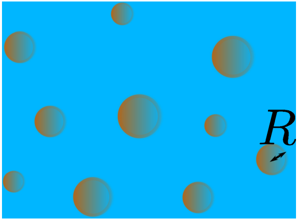


Everyday life :

$$k_B T \gg \rho g R^4$$

Colloids

Particles suspension

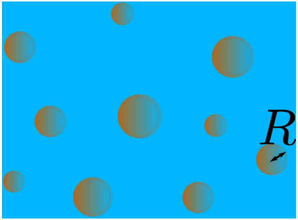


$$k_B T \gg \rho g R^4$$

Everyday life :

Colloids

Particles suspension



$$k_B T \gg \rho g R^4$$

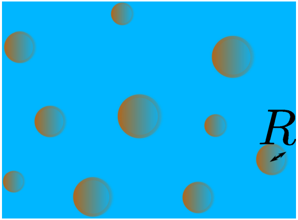
Everyday life :





Colloids

Particles suspension

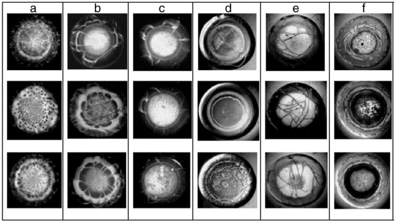


$$k_B T \gg \rho g R^4$$

Everyday life :

Colloids

Blood deposits : health indicator (?)

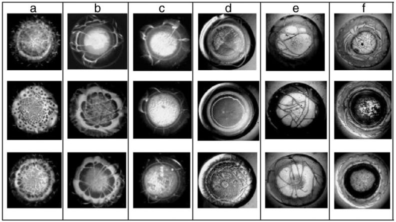


T.A. Yakhno *et al.*, IEEE Eng. Med. Biol. Mag., 24(2), 96 (2005)

- Important parameters ?
- Physical mechanisms ?
- ⇒ Study of colloids droplets evaporation

Colloids

Blood deposits : health indicator (?)

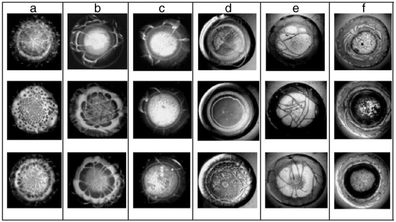


T.A. Yakhno *et al.*, IEEE Eng. Med. Biol. Mag., 24(2), 96 (2005)

- Important parameters ?
- Physical mechanisms ?
- ⇒ Study of colloids droplets evaporation

Colloids

Blood deposits : health indicator (?)

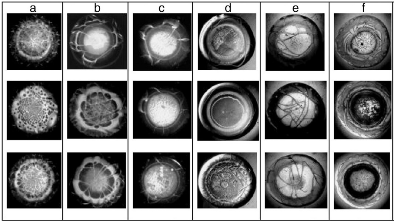


T.A. Yakhno *et al.*, IEEE Eng. Med. Biol. Mag., 24(2), 96 (2005)

- Important parameters ?
- Physical mechanisms ?
- ⇒ Study of colloids droplets evaporation

Colloids

Blood deposits : health indicator (?)



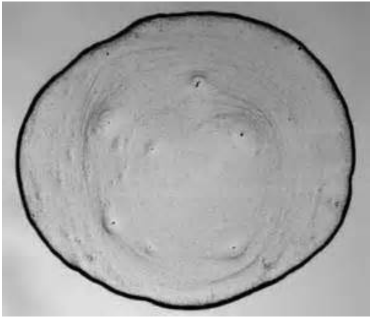
T.A. Yakhno *et al.*, IEEE Eng. Med. Biol. Mag., 24(2), 96 (2005)

- Important parameters ?
- Physical mechanisms ?
- $\Rightarrow$ Study of colloids droplets evaporation

Table of contents

Coffee Ring

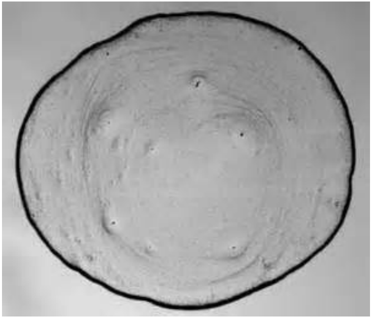
Dominant effect : coffee ring



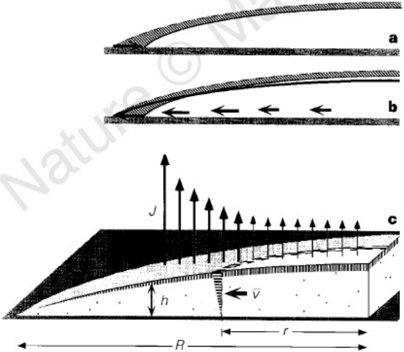
Robert D. Deegan *et al.*, Nature 3896653, p.827-829 (1997)

Coffee Ring

Dominant effect : coffee ring



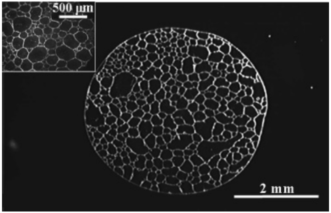
Pinning of contact line and evaporation profile



Robert D. Deegan *et al.*, Nature 3896653, p.827-829 (1997)

Marangoni effect

Temperature induced Marangoni stresses

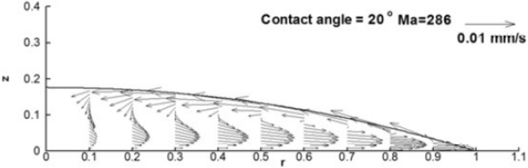


V.X. Nguyen and K.J. Stebe., PRL 8816, 164501 (2002)

Marangoni number for transition :

$$Ma = \frac{\frac{d\gamma}{dT}\ \triangle T\ t_f}{\eta\ R}$$

$$Ma_c \sim 10^2$$



H. Hu, and R.G. Larson. Langmuir 21, p.3972-3980 (2005)

Table of contents

PBS properties

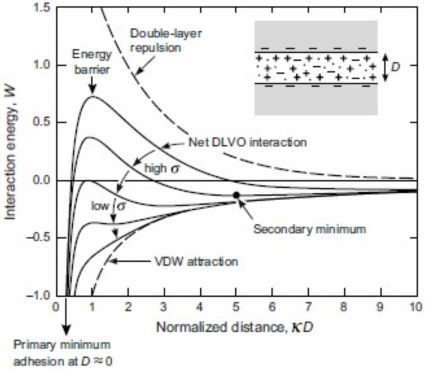
Phosphate-buffered saline (PBS) properties :

- pH Buffer (7.4)

PBS properties

Phosphate-buffered saline (PBS) properties :

- pH Buffer (7.4)
- Screen electrostatic repulsion

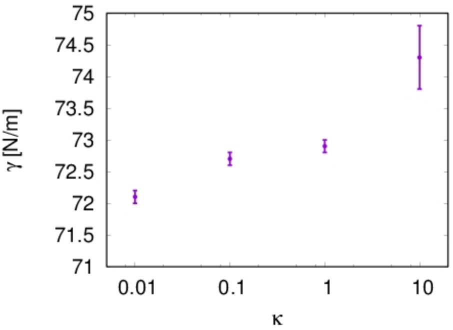


J.N. Israelachvili, *Intermolecular and surface forces* Academic press (2011).

PBS properties

Phosphate-buffered saline (PBS) properties :

- pH Buffer (7.4)
- Screen electrostatic repulsion
- Increase surface tension ($\frac{d\gamma}{d\kappa} \sim 10^{-4}$ N/m)



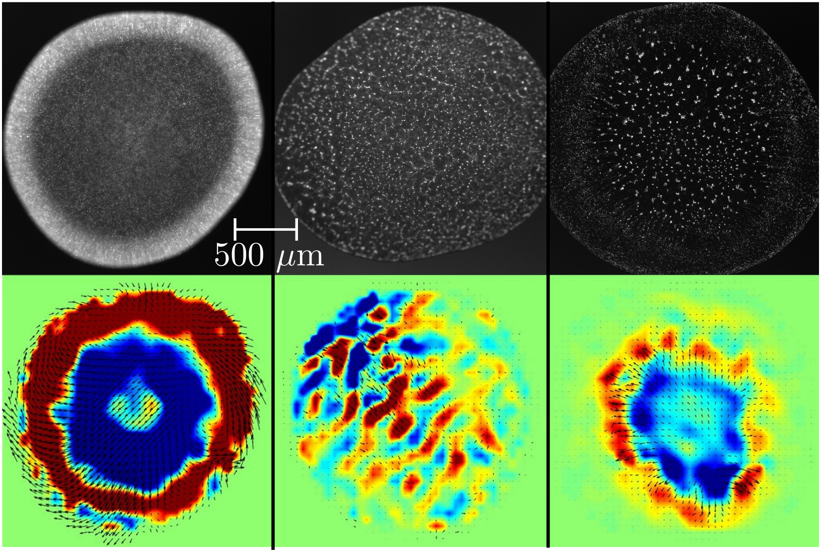
Pending drop measurements

Table of contents

PIV Movie

First, let's watch some movies!

Schematic view



Schematic view

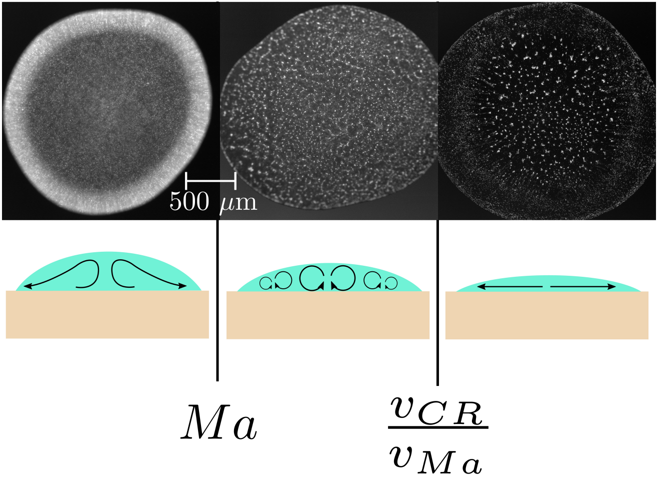
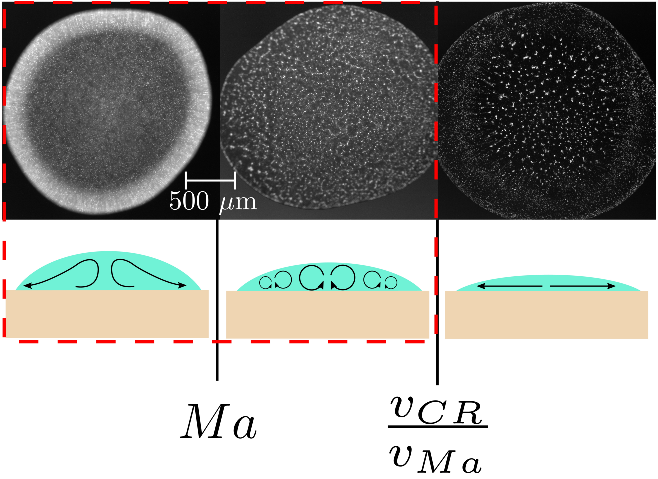
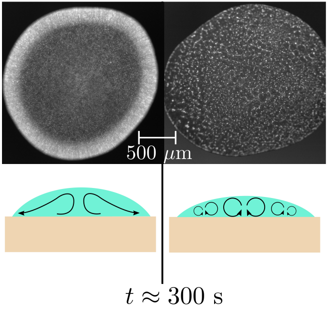


Table of contents

Marangoni transition



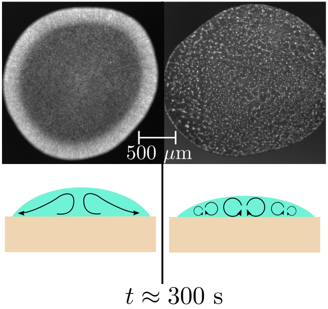
Marangoni transition



$t_f \approx 10^3$ $\frac{d\gamma}{d\kappa} \sim 10^{-4}$ $\eta \approx 10^{-3}$ $R \approx 10^{-3}$

Marangoni transition

$$\kappa \equiv \frac{C_i}{C_i(PBS)}$$

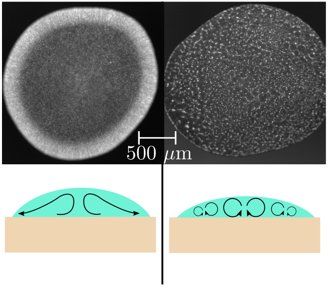


$t_f \approx 10^3$ $\frac{d\gamma}{d\kappa} \sim 10^{-4}$ $\eta \approx 10^{-3}$ $R \approx 10^{-3}$

Marangoni transition

$$\kappa \equiv \frac{C_i}{C_i(PBS)}$$

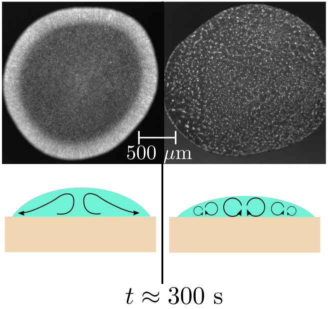
$$\kappa_0 \sim 10^{-2}$$



$t \approx 300$ s

$t_f \approx 10^3$ $\frac{d\gamma}{d\kappa} \sim 10^{-4}$ $\eta \approx 10^{-3}$ $R \approx 10^{-3}$

Marangoni transition



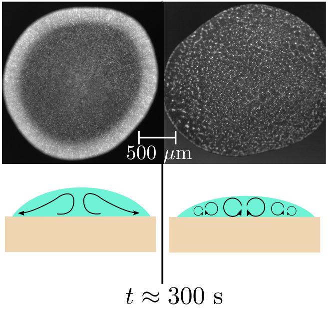
$t_f \approx 10^3$ $\frac{d\gamma}{d\kappa} \sim 10^{-4}$ $\eta \approx 10^{-3}$ $R \approx 10^{-3}$

$$\kappa \equiv \frac{C_i}{C_i(PBS)}$$

$$\kappa_0 \sim 10^{-2}$$

$$\kappa_m = \kappa_0 \frac{V_0}{V}$$

Marangoni transition

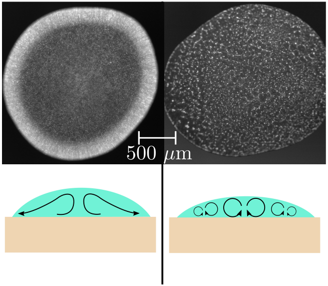


$t_f \approx 10^3$ $\frac{d\gamma}{d\kappa} \sim 10^{-4}$ $\eta \approx 10^{-3}$ $R \approx 10^{-3}$

$$\kappa \equiv \frac{C_i}{C_i(PBS)}$$
$$\kappa_0 \sim 10^{-2}$$
$$\kappa_m = \kappa_0 \frac{V_0}{V}$$

$$\triangle \kappa \sim \kappa_m - \kappa_0 = \kappa_0 (\frac{V_0}{V} - 1)$$

Marangoni transition



$t \approx 300$ s

$t_f \approx 10^3$ $\frac{d\gamma}{d\kappa} \sim 10^{-4}$ $\eta \approx 10^{-3}$ $R \approx 10^{-3}$

$$\kappa \equiv \frac{C_i}{C_i(PBS)}$$

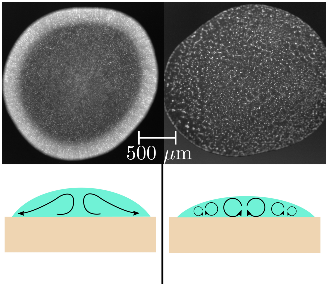
$$\kappa_0 \sim 10^{-2}$$

$$\kappa_m = \kappa_0 \frac{V_0}{V}$$

$$\triangle\kappa \sim \kappa_m - \kappa_0 = \kappa_0 (\frac{V_0}{V} - 1)$$

$$Ma = \frac{\frac{d\gamma}{d\kappa} \triangle\kappa \; t_f}{\eta \; R}$$

Marangoni transition



$t \approx 300$ s

$t_f \approx 10^3$ $\frac{d\gamma}{d\kappa} \sim 10^{-4}$ $\eta \approx 10^{-3}$ $R \approx 10^{-3}$

$$\kappa \equiv \frac{C_i}{C_i(PBS)}$$

$$\kappa_0 \sim 10^{-2}$$

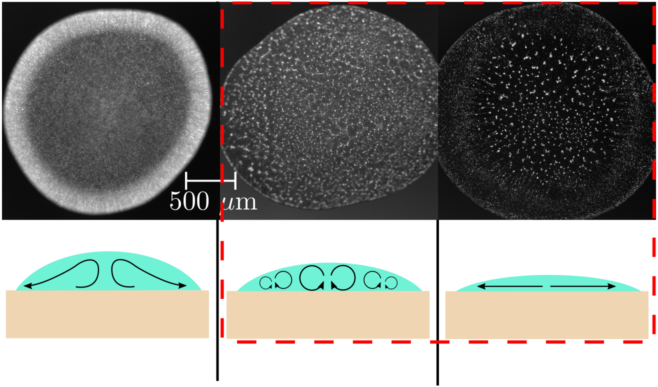
$$\kappa_m = \kappa_0 \frac{V_0}{V}$$

$$\triangle\kappa \sim \kappa_m - \kappa_0 = \kappa_0\left(\frac{V_0}{V} - 1\right)$$

$$Ma = \frac{\frac{d\gamma}{d\kappa} \triangle\kappa \; t_f}{\eta \; R}$$

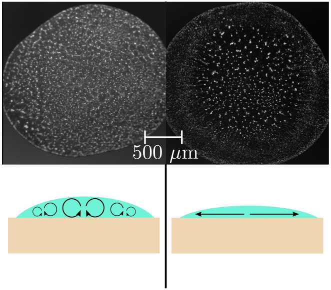
$$\Rightarrow Ma \sim 10^2 \sim Ma_c$$

Outward flow transition



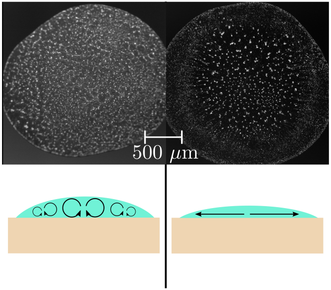
$$Ma \qquad \frac{v_{CR}}{v_{Ma}}$$

Outward flow transition



$$\frac{v_{CR}}{v_{Ma}}$$

Outward flow transition

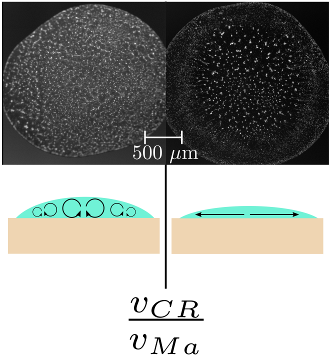


$$\frac{v_{CR}}{v_{Ma}}$$

$$v_r = v_{CR} + v_{Ma}$$

H. Hu, and R.G. Larson. Langmuir 21, p.3972-3980 (2005)

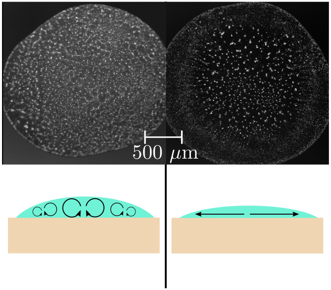
Outward flow transition



$$v_r = v_{CR} + v_{Ma}$$

$$\frac{v_{CR}}{v_{Ma}} \sim \frac{R^2}{Ma \ h^2}$$

Outward flow transition



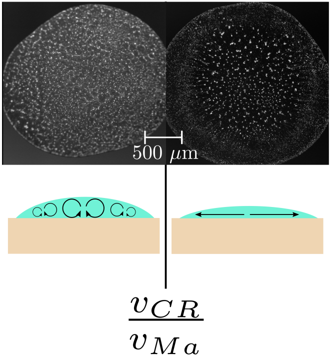
$$\frac{v_{CR}}{v_{Ma}}$$

$$v_r = v_{CR} + v_{Ma}$$

$$\frac{v_{CR}}{v_{Ma}} \sim \frac{R^2}{Ma\ h^2}$$

$$\Rightarrow v_{CR} \gg v_{Ma} \Leftrightarrow \frac{R^2}{h^2} \gg Ma$$

Outward flow transition



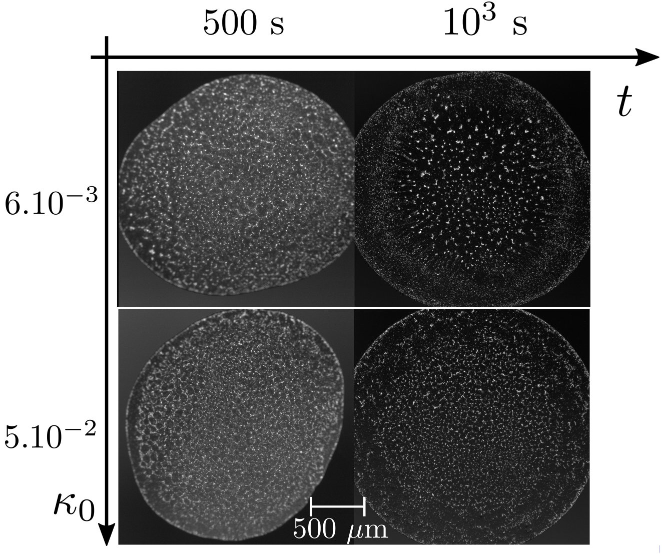
$$v_r = v_{CR} + v_{Ma}$$

$$\frac{v_{CR}}{v_{Ma}} \sim \frac{R^2}{Ma\ h^2}$$

$$\Rightarrow v_{CR} \gg v_{Ma} \Leftrightarrow \frac{R^2}{h^2} \gg Ma$$

Motion until $h \sim 10^{-6}$ and $R \approx 10^{-3}$, $Ma \sim 10^2$

Effect of PBS concentration



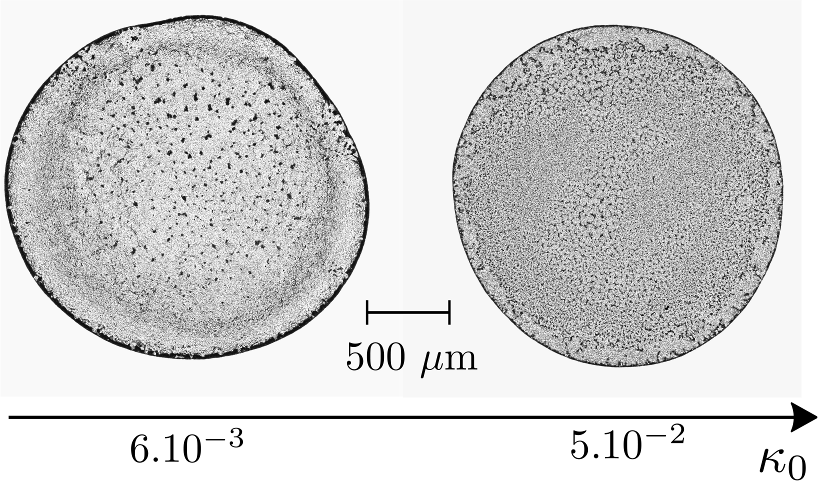
$Ma \propto \kappa_0$

PBS screens electrostatic repulsion

Table of contents

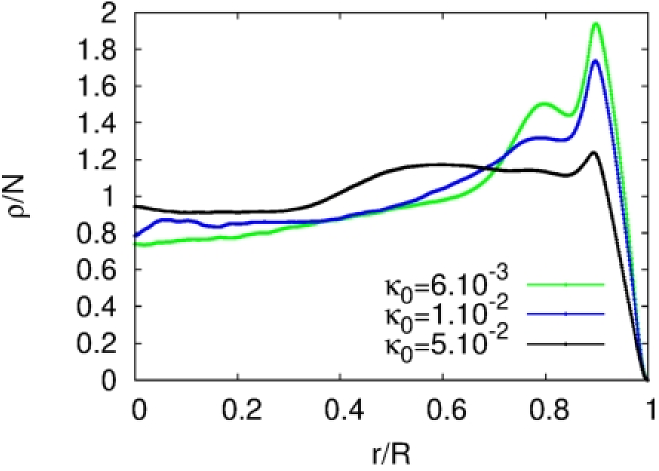
Effect of PBS concentration

Bright field pictures of dried drops :



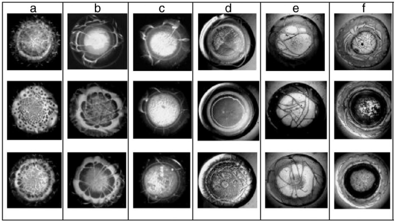
Effect of PBS concentration

Distribution of deposited particles :



Conclusion

Blood deposits : health indicator (?)

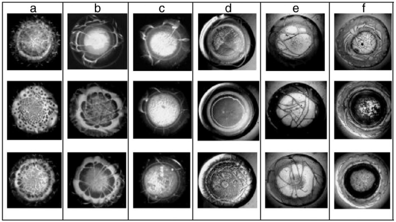


T.A. Yakhno *et al.*, IEEE Eng. Med. Biol. Mag., 24(2), 96 (2005)

- Important parameters ? Ionic concentration is one
- Physical mechanisms ? Competition Marangoni-Bénard vs Coffee-Ring

Conclusion

Blood deposits : health indicator (?)

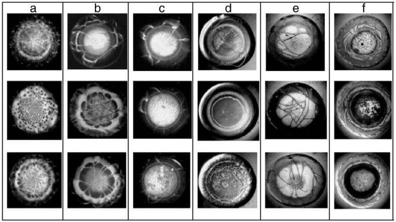


T.A. Yakhno *et al.*, IEEE Eng. Med. Biol. Mag., 24(2), 96 (2005)

- Important parameters ? **Ionic concentration is one**
- Physical mechanisms ? Competition Marangoni-Bénard vs Coffee-Ring

Conclusion

Blood deposits : health indicator (?)



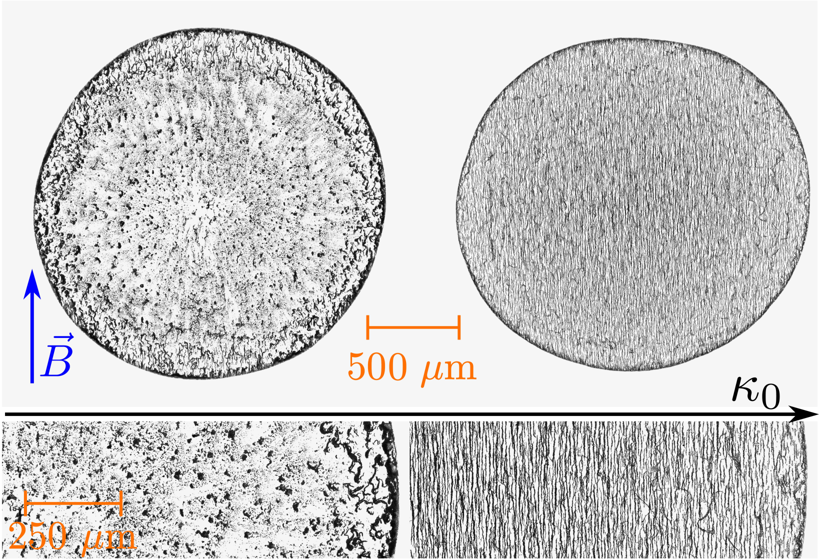
T.A. Yakhno *et al.*, IEEE Eng. Med. Biol. Mag., 24(2), 96 (2005)

- Important parameters ? **Ionic concentration is one**
- Physical mechanisms ? **Competition Marangoni-Bénard vs Coffee-Ring**

Prospects

- High PBS keeps Marangoni "honeycomb" patterns after drying
- Could it keep other structures ? e.g. self-assembled superparamagnetic colloids ?

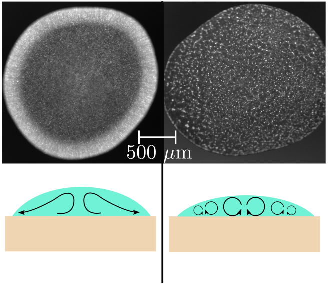
Prospects



Thanks !

Thanks for your attention !

Marangoni transition



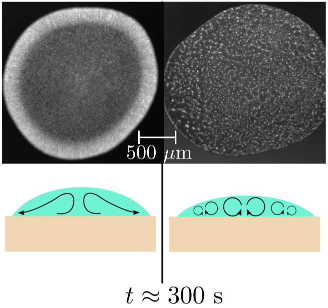
$t \approx 300$ s

$$Ma = \frac{\frac{d\gamma}{d\kappa} \ \triangle\kappa \ t_f}{\eta \ R} \approx 10^5 \triangle \kappa$$

$t_f \approx 10^3$ $\frac{d\gamma}{d\kappa} \sim 10^{-4}$ $\eta \approx 10^{-3}$ $R \approx 10^{-3}$

Marangoni transition

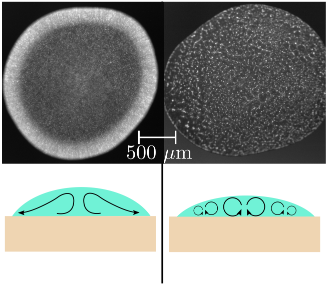
$$\kappa \equiv \frac{C_i}{C_i(PBS)}$$



$$Ma = \frac{\frac{d\gamma}{d\kappa} \; \triangle\kappa \; t_f}{\eta \; R} \approx 10^5 \triangle \kappa$$

$t_f \approx 10^3$ $\frac{d\gamma}{d\kappa} \sim 10^{-4}$ $\eta \approx 10^{-3}$ $R \approx 10^{-3}$

Marangoni transition



$$t \approx 300 \text{ s}$$

$$Ma = \frac{\frac{d\gamma}{d\kappa} \; \triangle\kappa \; t_f}{\eta \; R} \approx 10^5 \triangle \kappa$$

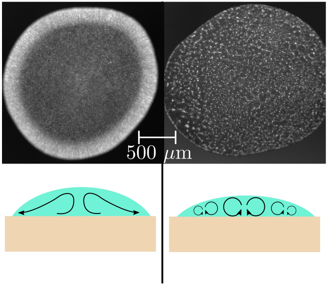
$t_f \approx 10^3$ $\frac{d\gamma}{d\kappa} \sim 10^{-4}$ $\eta \approx 10^{-3}$ $R \approx 10^{-3}$

$$\kappa \equiv \frac{C_i}{C_i(PBS)}$$

$$\kappa_0 \sim 10^{-2}$$

Marangoni transition

$$\kappa \equiv \frac{C_i}{C_i(PBS)}$$
$$\kappa_0 \sim 10^{-2}$$
$$\kappa_m = \kappa_0 \frac{V_0}{V}$$

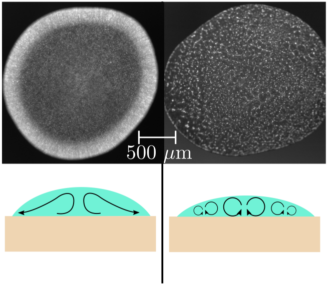


$$t \approx 300 \text{ s}$$

$$Ma = \frac{\frac{d\gamma}{d\kappa} \triangle\kappa \; t_f}{\eta \; R} \approx 10^5 \triangle \kappa$$

$t_f \approx 10^3$ $\frac{d\gamma}{d\kappa} \sim 10^{-4}$ $\eta \approx 10^{-3}$ $R \approx 10^{-3}$

Marangoni transition



$t \approx 300$ s

$$Ma = \frac{\frac{d\gamma}{d\kappa} \ \triangle\kappa \ t_f}{\eta \ R} \approx 10^5 \triangle \kappa$$

$t_f \approx 10^3$ $\frac{d\gamma}{d\kappa} \sim 10^{-4}$ $\eta \approx 10^{-3}$ $R \approx 10^{-3}$

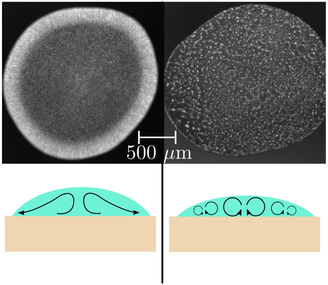
$$\kappa \equiv \frac{C_i}{C_i(PBS)}$$

$$\kappa_0 \sim 10^{-2}$$

$$\kappa_m = \kappa_0 \frac{V_0}{V}$$

$$\triangle \kappa \sim \kappa_m - \kappa_0 = \kappa_0 (\frac{V_0}{V} - 1)$$

Marangoni transition



$t \approx 300$ s

$$Ma = \frac{\frac{d\gamma}{d\kappa} \triangle\kappa \; t_f}{\eta \; R} \approx 10^5 \triangle \kappa$$

$t_f \approx 10^3 \; \frac{d\gamma}{d\kappa} \sim 10^{-4} \; \eta \approx 10^{-3} \; R \approx 10^{-3}$

$$\kappa \equiv \frac{C_i}{C_i(PBS)}$$

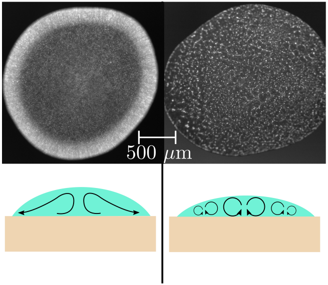
$$\kappa_0 \sim 10^{-2}$$

$$\kappa_m = \kappa_0 \frac{V_0}{V}$$

$$\triangle \kappa \sim \kappa_m - \kappa_0 = \kappa_0 \left(\frac{V_0}{V} - 1\right)$$

$$\sim \kappa_0 \left(\frac{t_f}{t_f - t} - 1\right) = \kappa_0 \frac{t}{t_f - t}$$

Marangoni transition



$t \approx 300$ s

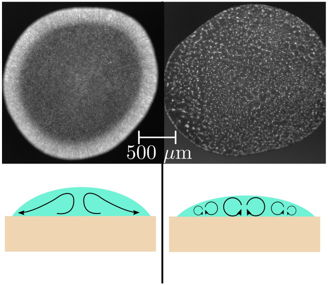
$$Ma = \frac{\frac{d\gamma}{d\kappa} \triangle\kappa \; t_f}{\eta \; R} \approx 10^5 \triangle \kappa$$

$t_f \approx 10^3$ $\frac{d\gamma}{d\kappa} \sim 10^{-4}$ $\eta \approx 10^{-3}$ $R \approx 10^{-3}$

$$\kappa \equiv \frac{C_i}{C_i(PBS)}$$
$$\kappa_0 \sim 10^{-2}$$
$$\kappa_m = \kappa_0 \frac{V_0}{V}$$

$$\triangle \kappa \sim \kappa_m - \kappa_0 = \kappa_0(\frac{V_0}{V} - 1)$$
$$\sim \kappa_0(\frac{t_f}{t_f - t} - 1) = \kappa_0 \frac{t}{t_f - t}$$
$$\sim 10^{-3}$$

Marangoni transition



$t \approx 300$ s

$$Ma = \frac{\frac{d\gamma}{d\kappa} \triangle\kappa \; t_f}{\eta \; R} \approx 10^5 \triangle \kappa$$

$t_f \approx 10^3$ $\frac{d\gamma}{d\kappa} \sim 10^{-4}$ $\eta \approx 10^{-3}$ $R \approx 10^{-3}$

$$\kappa \equiv \frac{C_i}{C_i(PBS)}$$

$$\kappa_0 \sim 10^{-2}$$

$$\kappa_m = \kappa_0 \frac{V_0}{V}$$

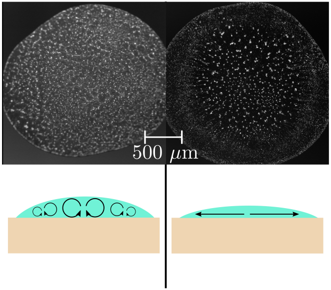
$$\triangle \kappa \sim \kappa_m - \kappa_0 = \kappa_0 \left(\frac{V_0}{V} - 1\right)$$

$$\sim \kappa_0 \left(\frac{t_f}{t_f - t} - 1\right) = \kappa_0 \frac{t}{t_f - t}$$

$$\sim 10^{-3}$$

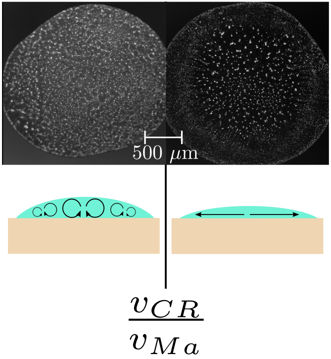
$$\Rightarrow Ma \sim 10^2 \sim Ma_c$$

Outward flow transition



$$\frac{v_{CR}}{v_{Ma}}$$

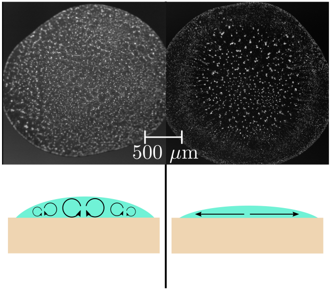
Outward flow transition



$$v_r = v_{CR} + v_{Ma}$$

H. Hu, and R.G. Larson. Langmuir 21, p.3972-3980 (2005)

Outward flow transition

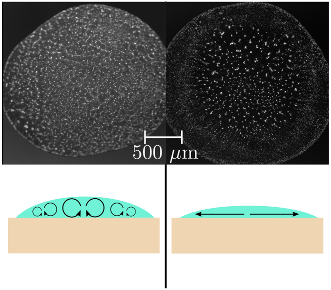


$$\frac{v_{CR}}{v_{Ma}}$$

$$v_r = v_{CR} + v_{Ma}$$

$$v_{Ma} \sim \frac{Ma\ h\ h_0}{R\ t_f}$$

Outward flow transition

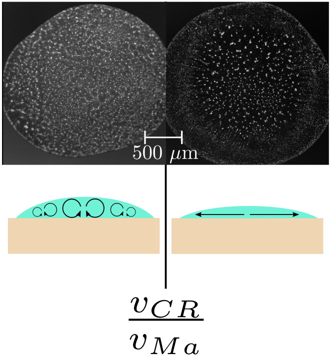


$$v_r = v_{CR} + v_{Ma}$$

$$v_{Ma} \sim \frac{Ma\ h\ h_0}{R\ t_f}$$

$$v_{CR} \sim \frac{2\ h_0\ R}{h\ t_f}$$

Outward flow transition



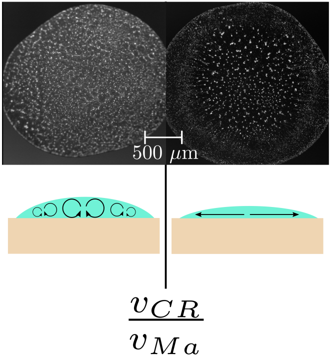
$$v_r = v_{CR} + v_{Ma}$$

$$v_{Ma} \sim \frac{Ma\ h\ h_0}{R\ t_f}$$

$$v_{CR} \sim \frac{2\ h_0\ R}{h\ t_f}$$

$$\frac{v_{CR}}{v_{Ma}} \sim \frac{R^2}{Ma\ h^2}$$

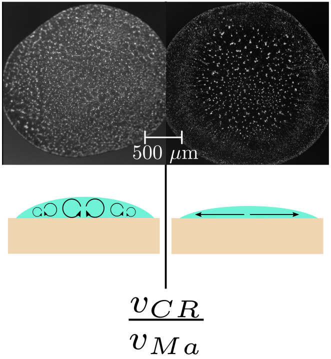
Outward flow transition



$$v_r = v_{CR} + v_{Ma}$$

$$v_{Ma} \sim \frac{Ma \; h \; h_0}{R \; t_f}$$
$$v_{CR} \sim \frac{2 \; h_0 \; R}{h \; t_f}$$
$$\frac{v_{CR}}{v_{Ma}} \sim \frac{R^2}{Ma \; h^2}$$
$$\Rightarrow v_{CR} \gg v_{Ma} \Leftrightarrow \frac{R^2}{h^2} \gg Ma$$

Outward flow transition



$$v_r = v_{CR} + v_{Ma}$$

$$v_{Ma} \sim \frac{Ma\ h\ h_0}{R\ t_f}$$
$$v_{CR} \sim \frac{2\ h_0\ R}{h\ t_f}$$
$$\frac{v_{CR}}{v_{Ma}} \sim \frac{R^2}{Ma\ h^2}$$
$$\Rightarrow v_{CR} \gg v_{Ma} \Leftrightarrow \frac{R^2}{h^2} \gg Ma$$

Motion until $h \sim 10^{-6}$ and $R \approx 10^{-3}$, $Ma \sim 10^2$