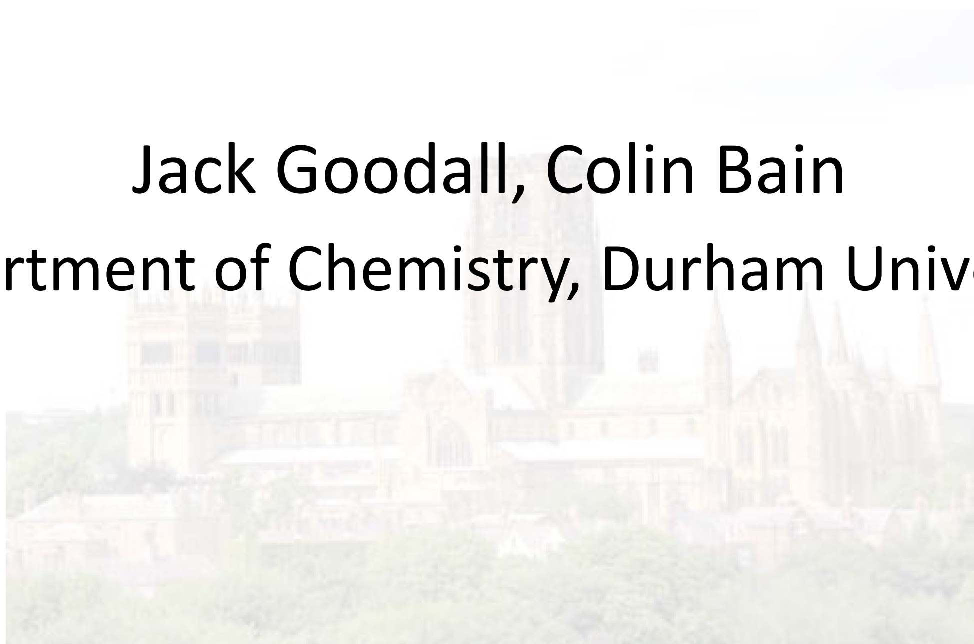
Particle Migration in Inkjet Printed Droplets

Jack Goodall, Colin Bain

Department of Chemistry, Durham University



Why Drops?

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Drying drops useful in many situations

- Graphics printing
- Printed electronics
- Crop spraying
- Coatings
- Biosensors
- 3D printing

Inkjet Printing

Not just desktop printers!

- High resolution
- Localised
- Low-waste
- Contact-free

The Coffee Ring Effect

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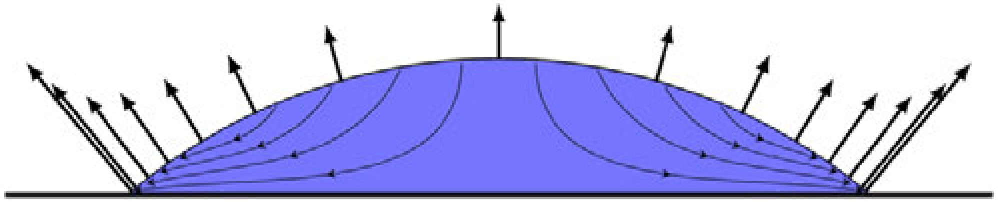
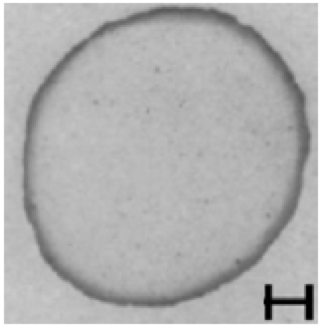


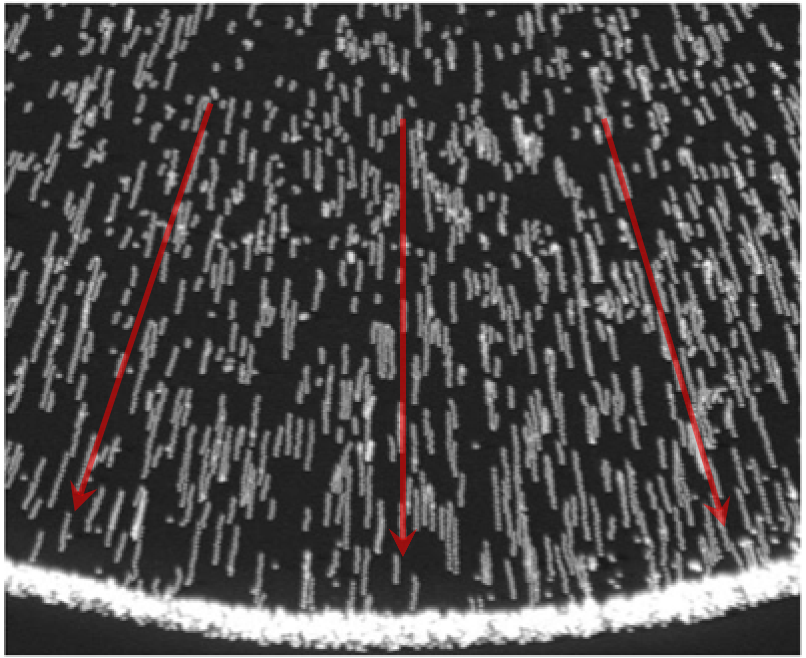
Simple requirements:

- Volatile fluid (evaporation!)
- Pinned contact line (uneven evaporative flux)

$\Rightarrow$ Convective flow

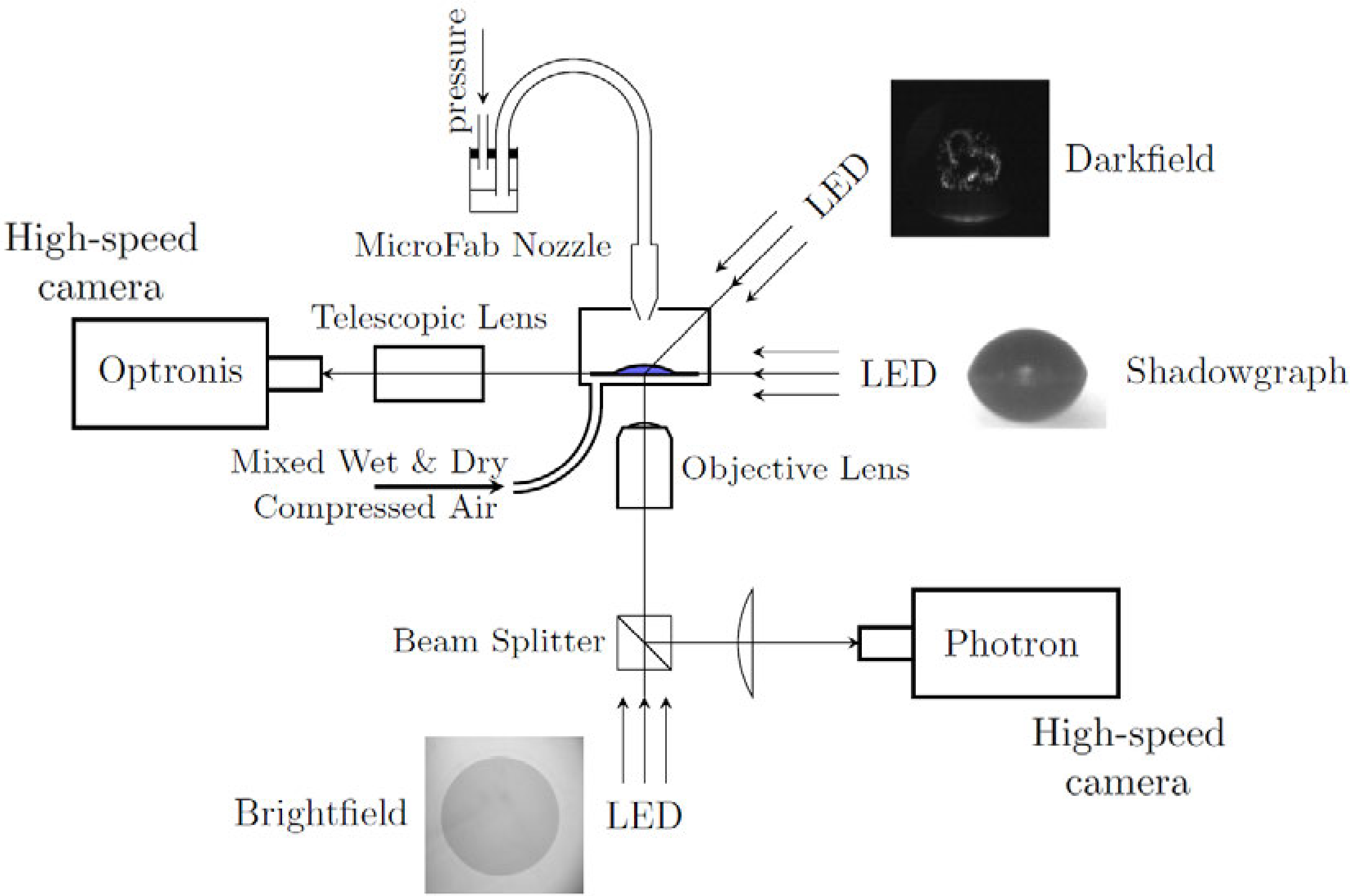
$\Rightarrow$ **Ring stain**





Deegan *et al.*, *Nature*, 1997, **389**, 827–829.
Deegan *et al.*, *Phys. Rev. E*, 2000, **62**, 756–765.

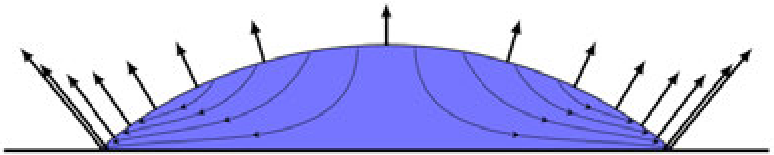
Experimental Setup



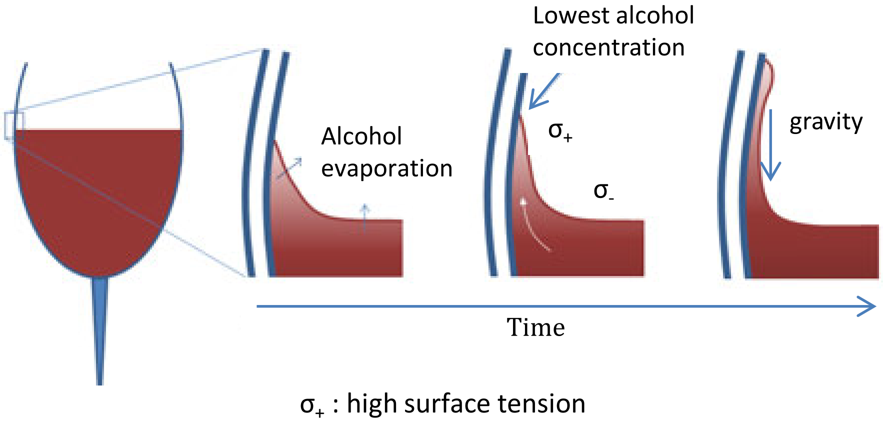
Binary Solvent Mixtures

Different solvents have different vapour pressures and surface tensions.

⇒ Concentration gradients



⇒ Surface tension gradients ⇒ Marangoni stresses



Tears of Wine and the Marangoni Effect, *Comsol Blogs*, (accessed 11 May 2018).

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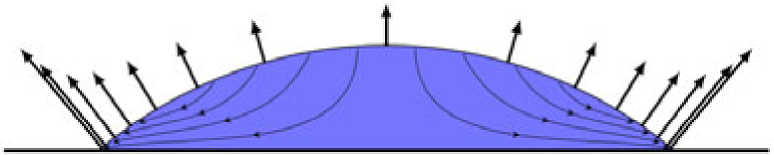


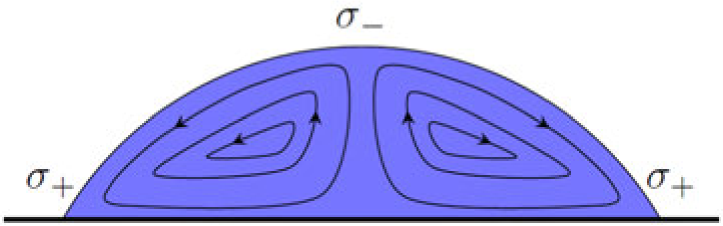
$\Rightarrow$ Concentration gradients

$\Rightarrow$ Surface tension gradients $\Rightarrow$ Marangoni stresses

$\Rightarrow$ **Internal Flows**

More volatile solvent has *lower* surface tension

More volatile solvent has *higher* surface tension



Ethanol – Water Mixture

Ethylene Glycol – Water Mixture

Ethanol-Water Droplet

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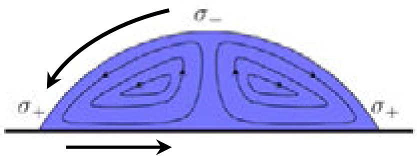
50 μm



Playback slowed down ~44 ×
First 35% of drying shown.

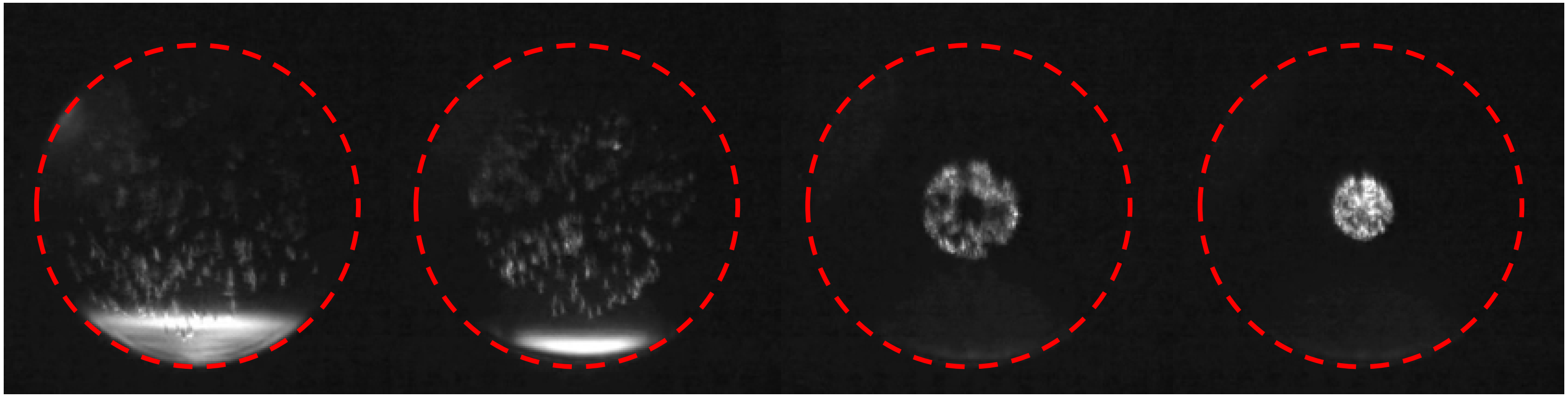
$V = 180$ pL
$\theta = 34\,°$
$R = 70$ μm

50%v Ethanol
50%v Water

0.015%v 1 μm Sterically stabilised polystyrene particles

Particle Migration

$0.03\ t_{dry}$ $0.17\ t_{dry}$ $0.29\ t_{dry}$ $0.31\ t_{dry}$



50 μm

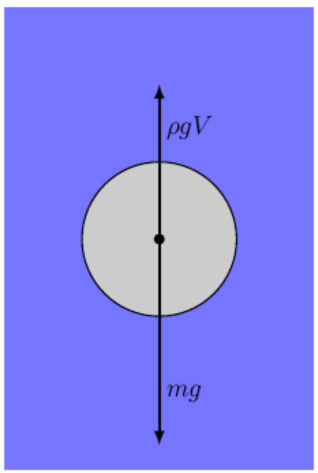
$R_{\text{Collected Group}} \sim R/10$

Possible Mechanisms?

Particles have low Reynolds Numbers so would be expected to follow streamlines rather than migrate.

Possible Mechanisms?

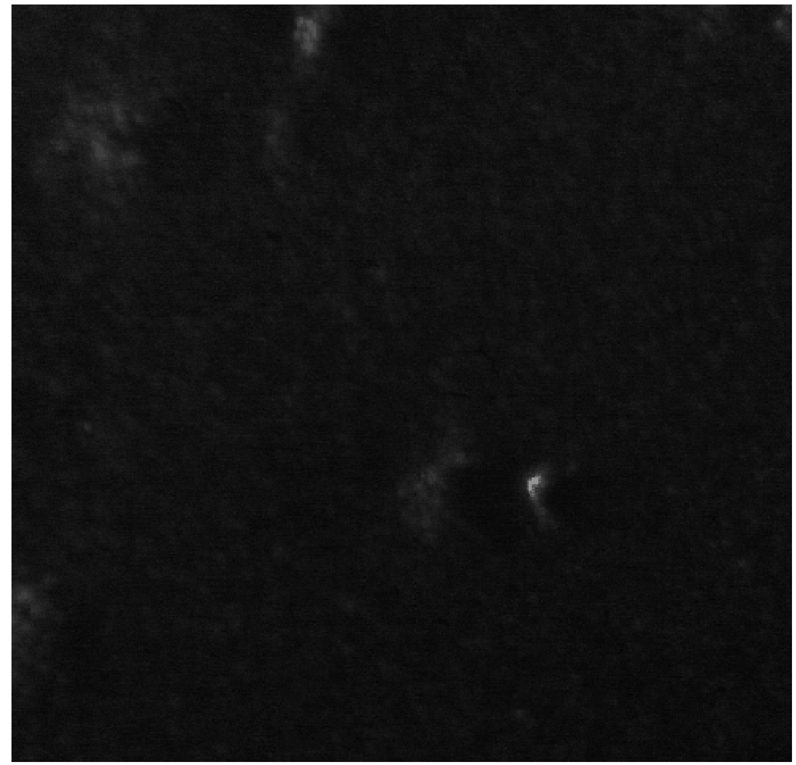
- Hydrodynamic
  - Buoyancy
  - Shear Induced



50%v Ethanol
50%v Water

0.5%v	3 μm
0.01%v	1 μm
0.05%v	600 nm
0.5%v	200 nm

PS spheres



Collected Group Radius Scales as $a^{0.25}$

E. L. Talbot, Doctoral, Durham University, 2014.

Possible Mechanisms?

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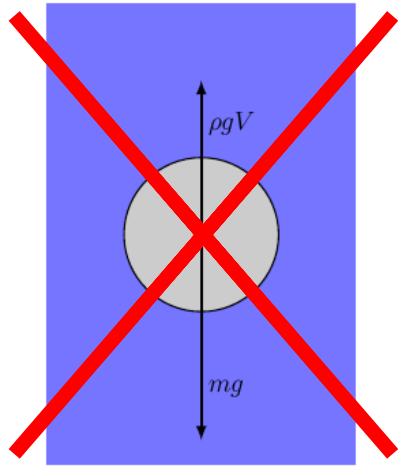
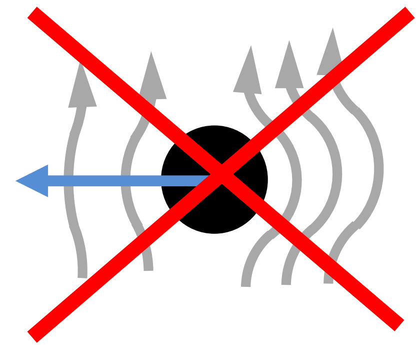
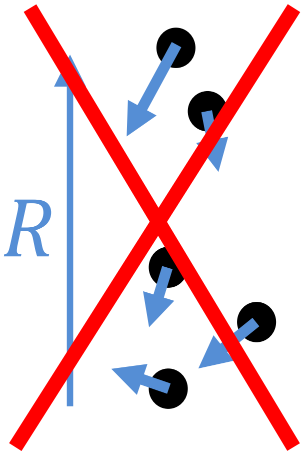
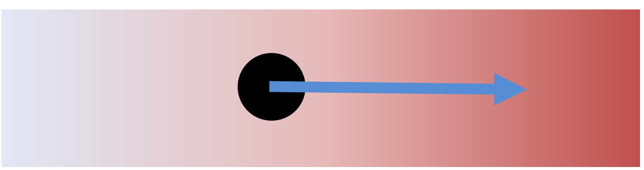




- Collisions





- Diffusiophoresis

Reverse the concentration gradient!

Ethanol Vapour

Water + 0.02%v 1 μm PS
Playback slowed down ~17×
$V = 200$ pL

50 μm

50%v Ethanol
50%v Water + 0.02%v 1 μm PS
Playback slowed down ~13×
$V = 155$ pL

Ethanol Vapour

Water + 0.02%v 1 µm PS
Playback slowed down ~17×
$V = 200$ pL

50 µm

50%v Ethanol
50%v Water + 0.02%v 1 µm PS
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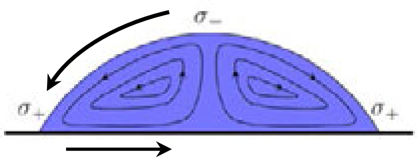
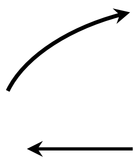
$V = 155$ pL

Tertiary Mixtures

50 μm



Switch



$V = 200$ pL
$\theta = 37$ °
$R = 71$ μm

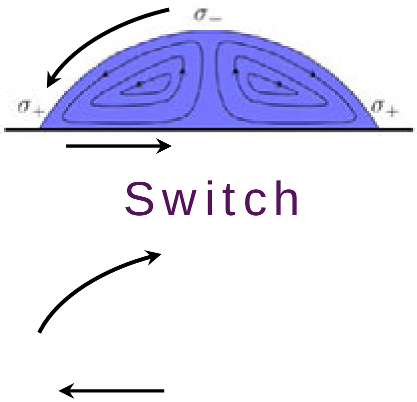
32%v Ethylene Glycol
34%v Ethanol
34%v Water

0.036%v 1 μm
Sterically stabilised
polystyrene particles

Playback slowed down ~11 ×
First 1.4% of drying shown.

Tertiary Mixtures

50 μm



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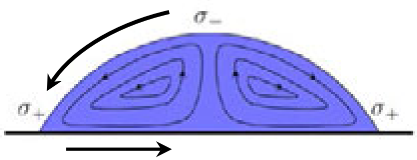

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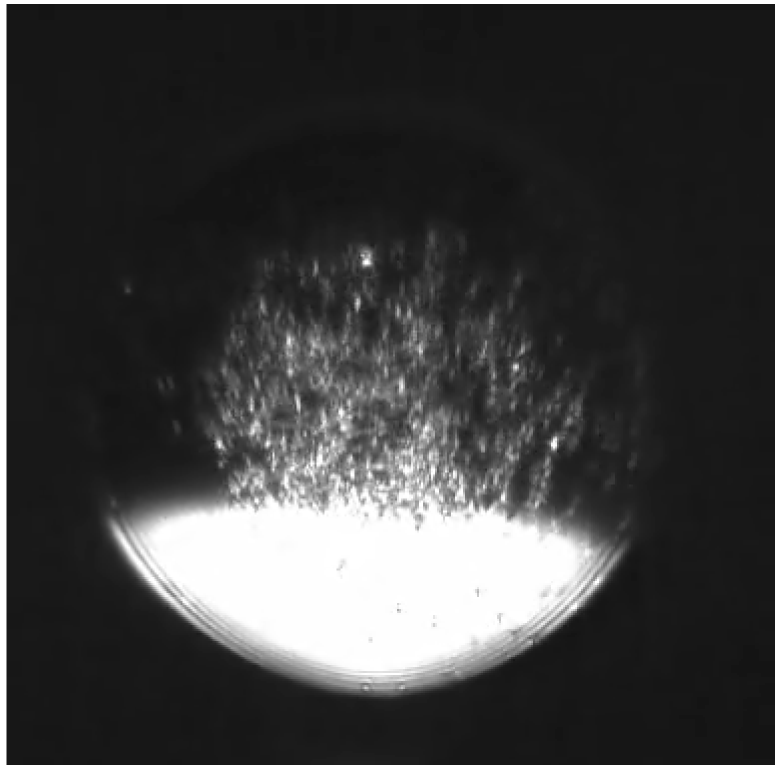

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Solutes

The concentration gradient doesn't need to be of a solvent.

Simple salts like sodium chloride (NaCl) or nitrate ($NaNO_3$) exhibit migration, as does

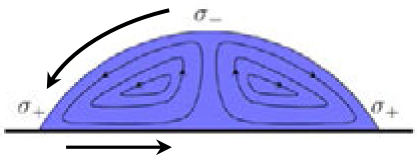
Sucrose

- *Highly* viscous at high concentrations
- Humectant.

Power *et al.*, *Chem. Sci.*, 2013, **4**, 2597–2604.

Sucrose

50 µm



Playback slowed down ~6×

$V = 330$ pL
$\theta = 40$ °
$R = 80$ µm

Water
16 wt% Sucrose

0.015%v 1 µm Sterically stabilised polystyrene particles

Conclusions

- Particle migration in solvent mixtures
- Particle migration in solutions
- Weak particle size dependence
- Not linked to Marangoni flows.

www.droplets2019.co.uk

DROPLETS

2019 - Durham, UK

16th - 18th September

Liquid droplets are important in many natural phenomena as well as for a broad variety of industrial processes. The aim of the 3-day international conference Droplets 2019 is to bring together physicists, chemists, mathematicians and engineers working on droplets in the broad sense: from pure to complex fluids; from impact to evaporation; in aerosols, emulsions or on surfaces; covering experimental, theoretical, and industrial perspectives.

The workshop builds upon the successful Droplets workshops held in 2013, 2015 and 2017, and will consist of plenary lectures, keynote lectures, oral presentations and poster sessions. The programme will be shaped to stimulate group discussions and informal exchanges.

SESSION TOPICS :

- Impact
- Wetting
- Coalescence and break-up
- Aerosols
- Liquid crystals and complex fluids
- Modelling across time and length scales
- Emulsions/Multiphase flow
- Microfluidics and Acoustofluidics
- Evaporation
- Textured, patterned, smart surfaces
- Inkjet printing

PLENARY SPEAKERS:

- **Pr. Vicki Grassian** *(University of California, San Diego)*
- **Pr. Detlef Lohse** *(University of Twente)*
- **Pr. Omar Matar** *(Imperial College)*
- **Pr. Sigurdur Thoroddsen** *(King Abdullah University)*

IMPORTANT DEADLINES:

- Abstract submission: **by 17 March 2019**
- Early bird registration: **by 30 June 2019**

Durham University

Northumbria University NEWCASTLE

Acknowledgements

Baingroup

Evaporative Drying of Droplets and the Formation of Micro-structured and Functional Particles and Films
EP/N025245/1

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