Fluid flows driven by sound and their applications

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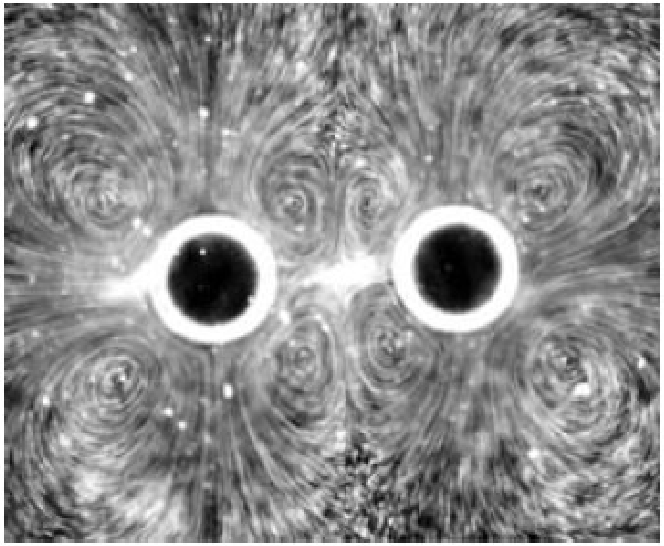

1. Mean flows driven by fluid oscillations

Co-authors

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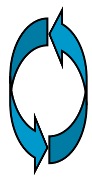
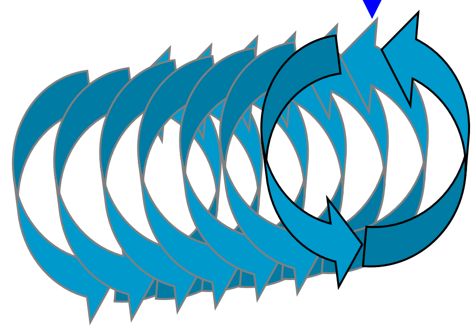
1. Mean flows driven by fluid oscillations

Conservation of momentum in liquid (Euler)

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} = -\frac{1}{\rho}\frac{\partial p}{\partial r}$$

Linear (small amplitude) oscillation





Nonlinear oscillation gives a net drift

Any fluid will *rectify* oscillation, giving *mean streaming*

2nd order mean flow velocities are always much lower in magnitude than 1st order oscillatory flow velocities

But the mean flows *keep going*, so we can see them, unlike the oscillatory flows which cancel out

1.1. Acoustic Streaming and Microstreaming

To create a net drift, the nonlinear term must exist. Thus, a **gradient** in the acoustic field must exist.

Streaming is significant if:

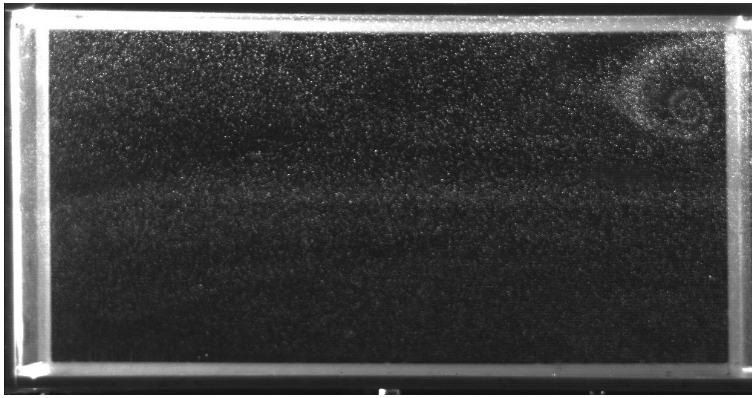
- power is high (gradient provided by dissipation or spreading) → **Acoustic Streaming**

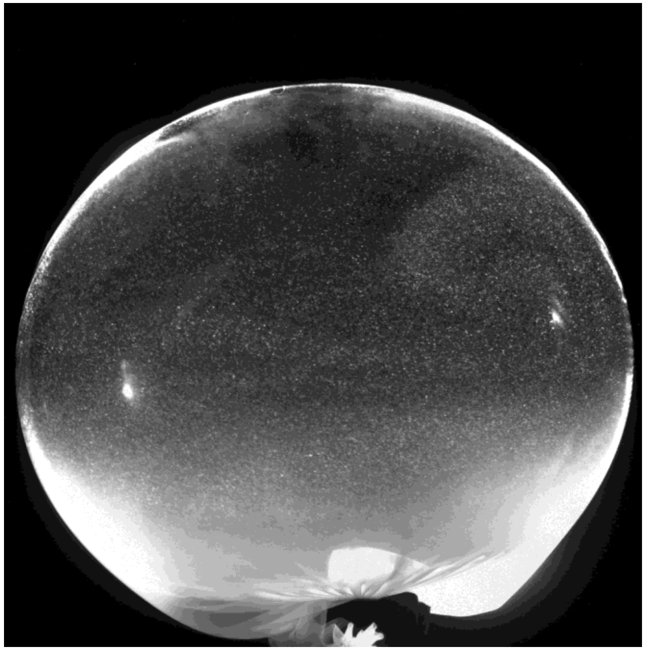
and/or

- gradient is high → Acoustic Microstreaming

2. Acoustic Streaming

Ovarian cysts





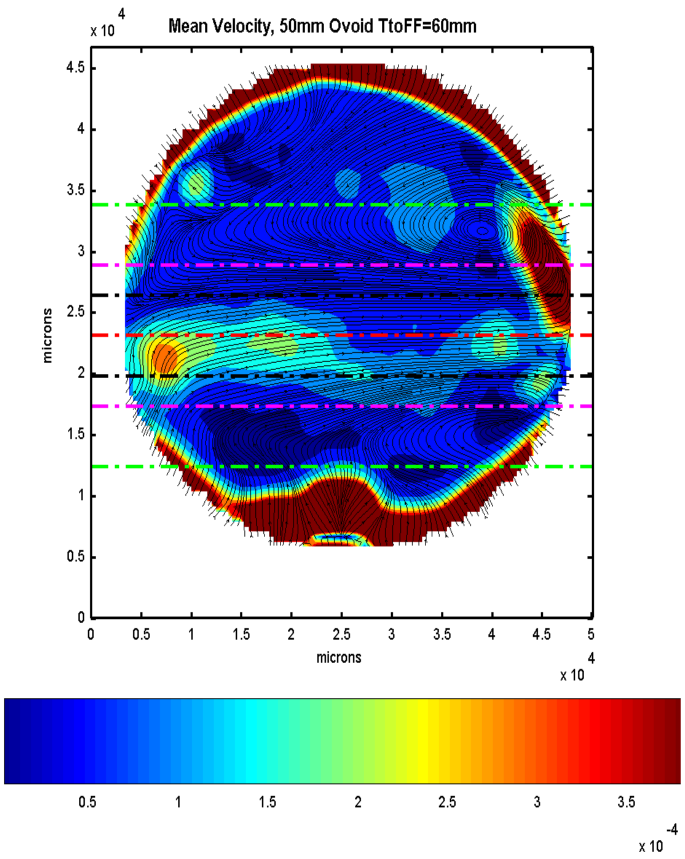
Experimental variations

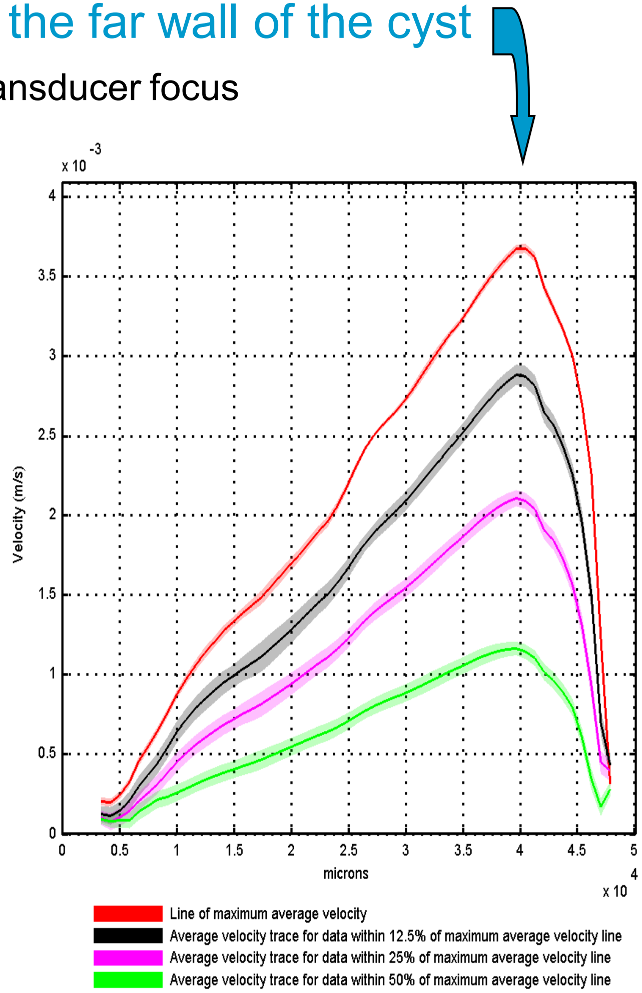
- Regular geometric shapes of various types (cylinders, boxes) and ovoid shapes investigated
- Different sizes, aspect ratios and angles to the transducer beam were investigated – 31 combinations, with dimensions ranging from a few mm to 12 cm

2.1. Acoustic Streaming in medical diagnostics

Velocity profiles generally show a jet at the far wall of the cyst

… provided the cyst near face is in <u>front</u> of the transducer focus





1.1. Acoustic Streaming and Microstreaming

To create a net drift, the nonlinear term must exist. Thus, a **gradient** in the acoustic field must exist.

Streaming is significant if:

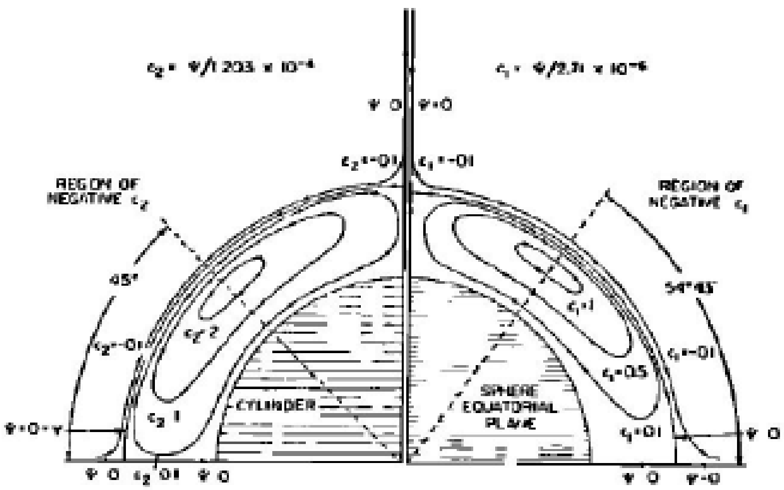
- gradient is high

→ **Acoustic Microstreaming**

3.1. Acoustic microstreaming and bubbles

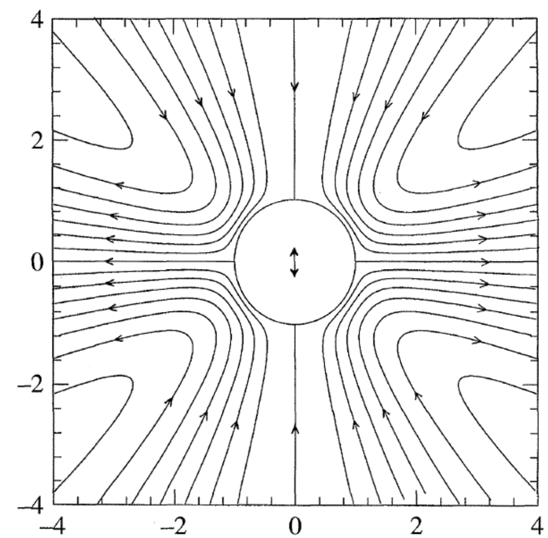
- ***Primary vortices:*** flow within the *Stokes boundary* or *shear wave* layer
- ***Secondary vortices*** flow outside boundary layer

$$\delta = \sqrt{2\nu/\Omega}$$



Primary vortices

Lane 1955, *JASA* **27**, 1082

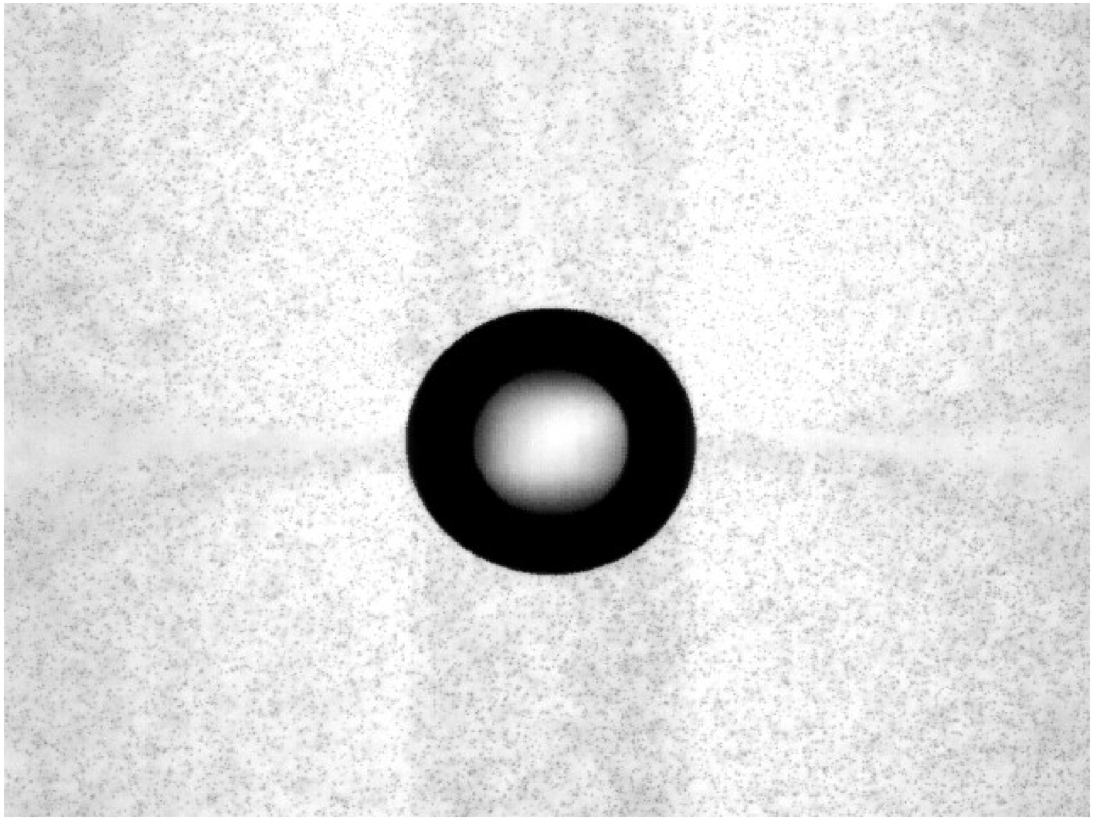


Secondary vortices

Longuet-Higgins 1998, *Proc.RSL. A*, **454**, 72574

Cavitation microstreaming

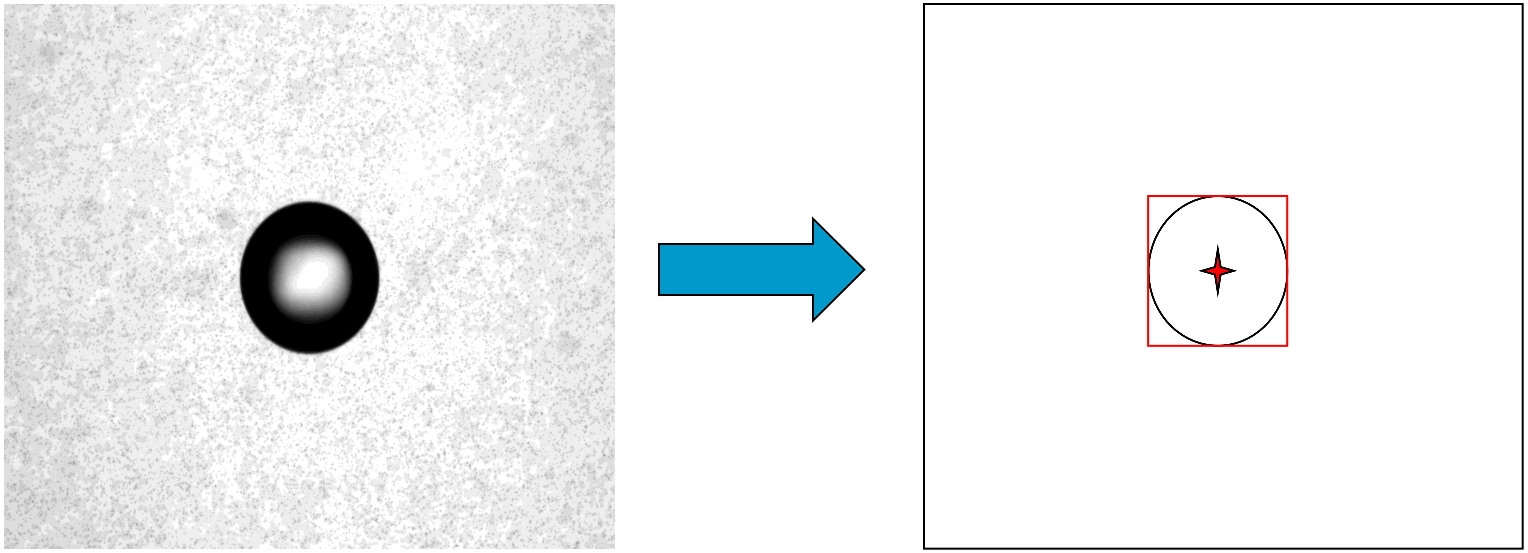
- Acoustic microstreaming observed around oscillating bubbles
- The flow is observed as a system of vortices around the bubble



Tho, P., Manasseh, R., Ooi, A., 2007, *J. Fluid Mech.* 576, 191-233.

Measuring bubble motion

- Apply an edge detection algorithm to image of bubble
- Take binary image data and determine centroid of image and radius



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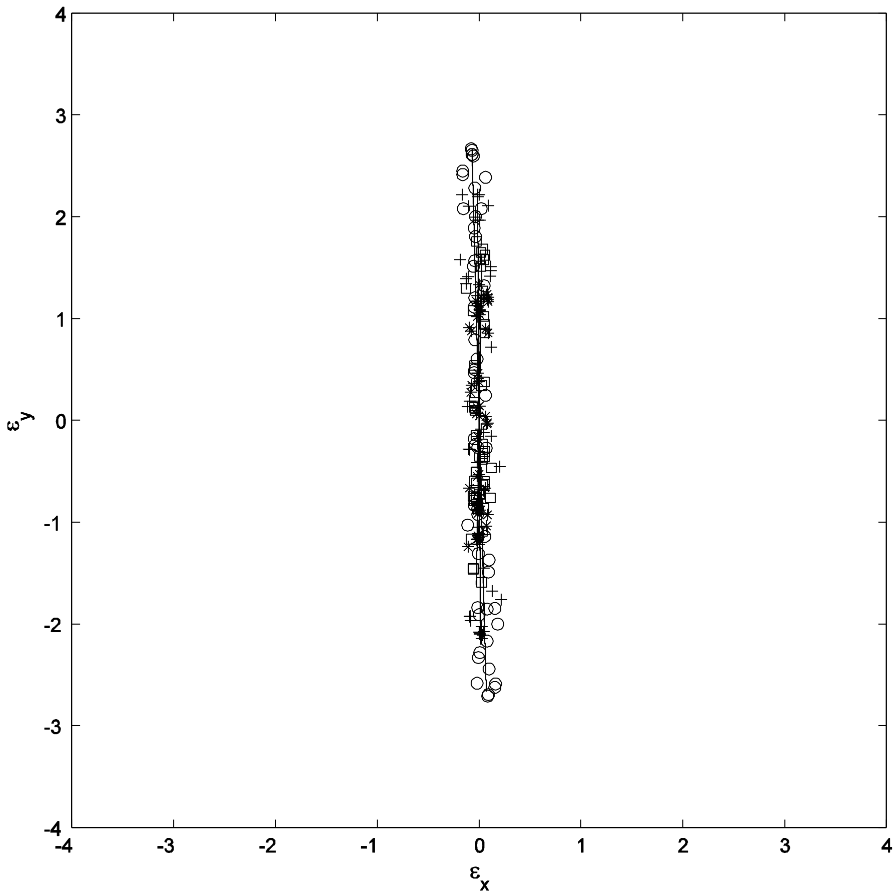
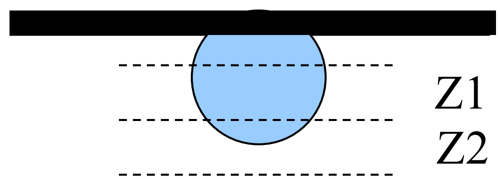
3.1. Acoustic microstreaming and bubbles

Linear translation

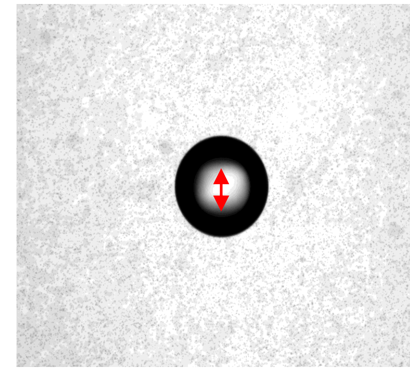


3.2. Acoustic microstreaming patterns

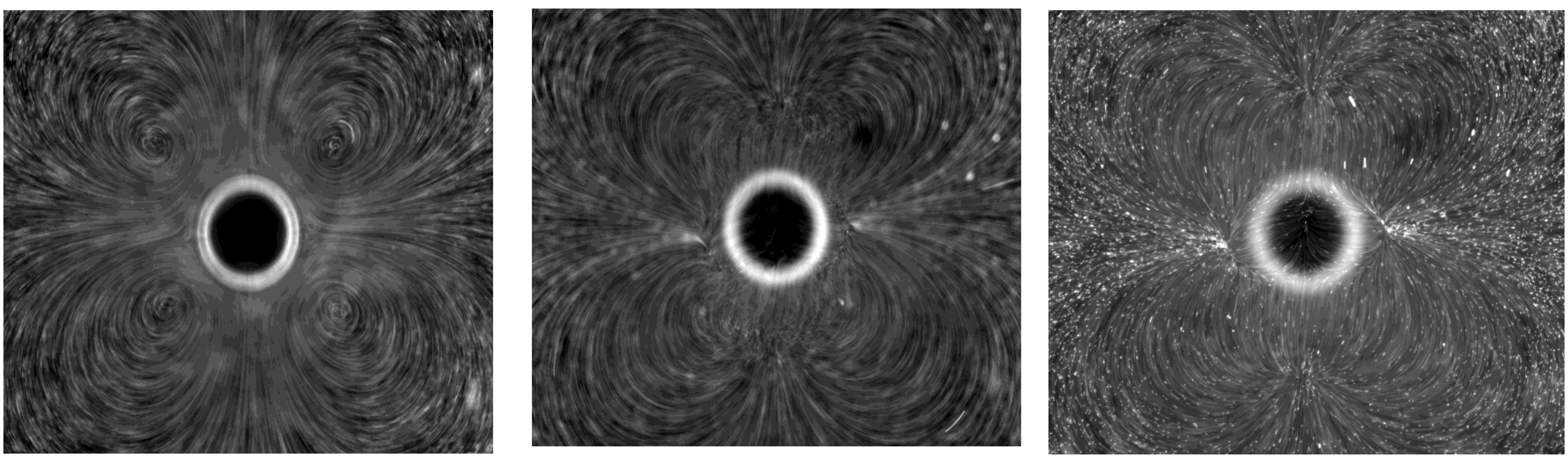
Linear translation



Z1 = 75 microns
Z2 = 250 microns
Z3 = 575 microns

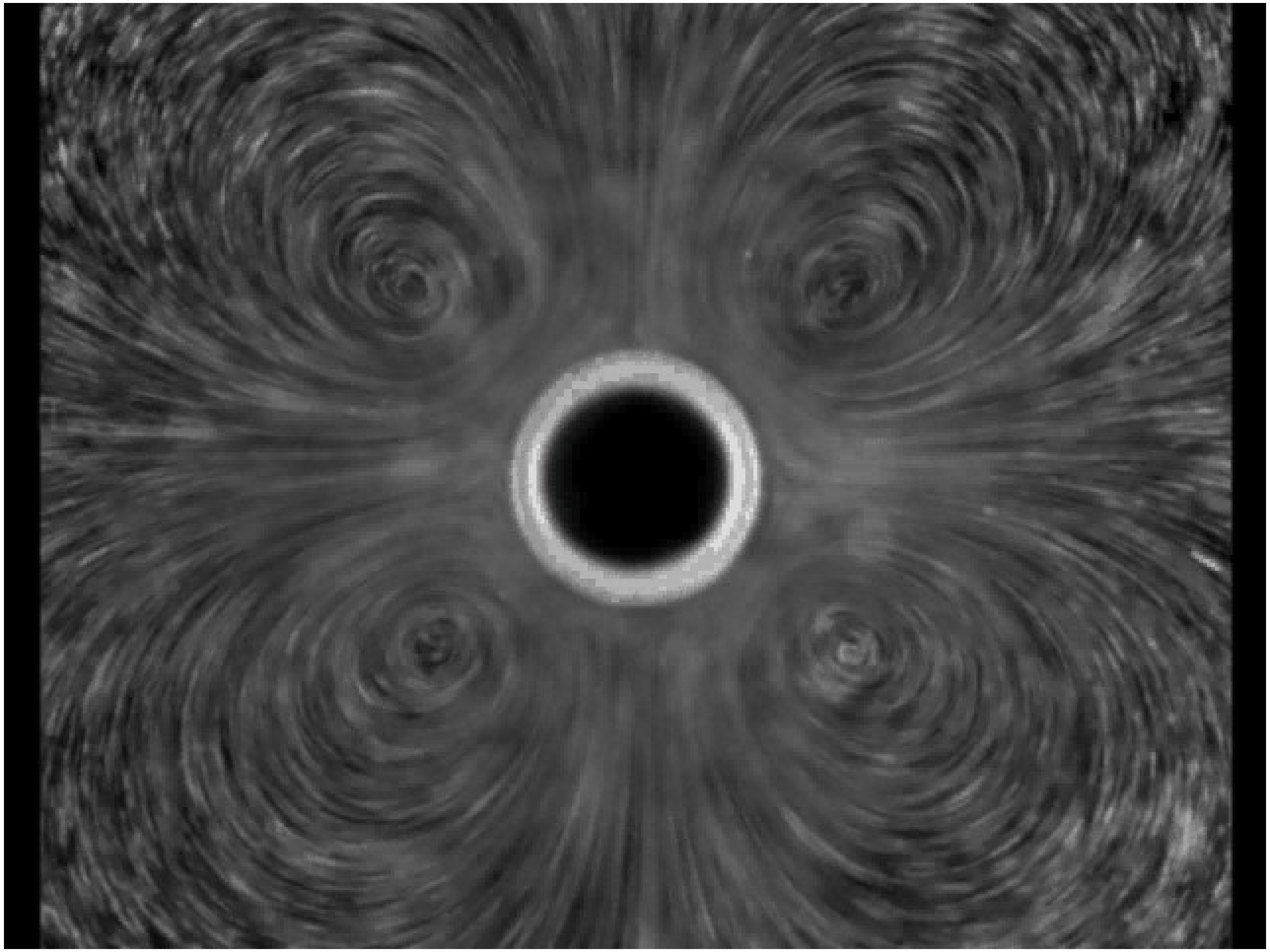


Streak photos show
3D flow



Tho, P., Manasseh, R., Ooi, A., 2007, *J. Fluid Mech.* 576, 191-233.

3.2. Acoustic microstreaming patterns



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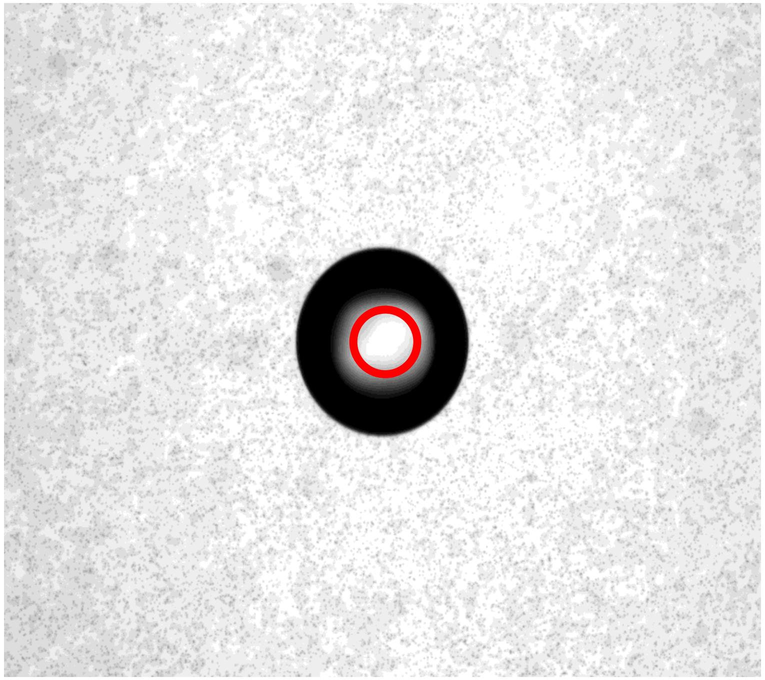
3.2. Acoustic microstreaming patterns

Circular orbit

- A circular orbit
- Bubble moves in anticlockwise manner



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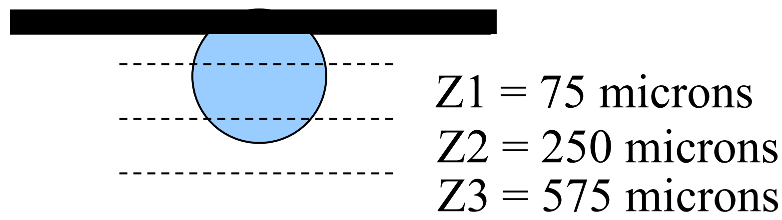
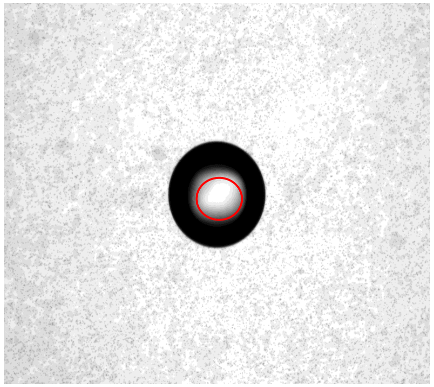
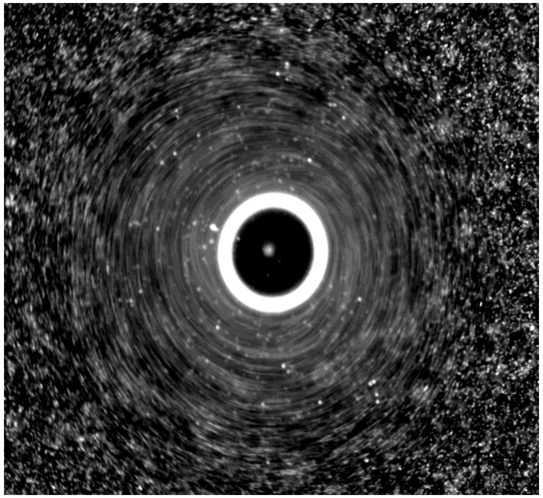
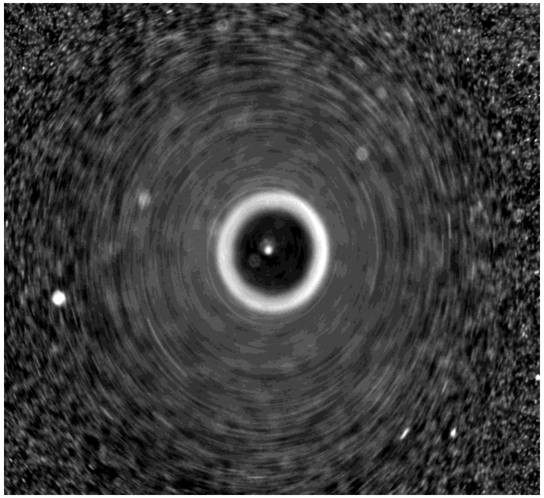
3.2. Acoustic microstreaming patterns

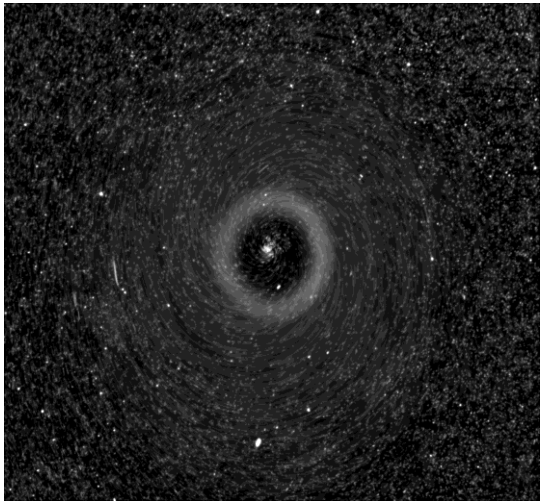
Circular orbit











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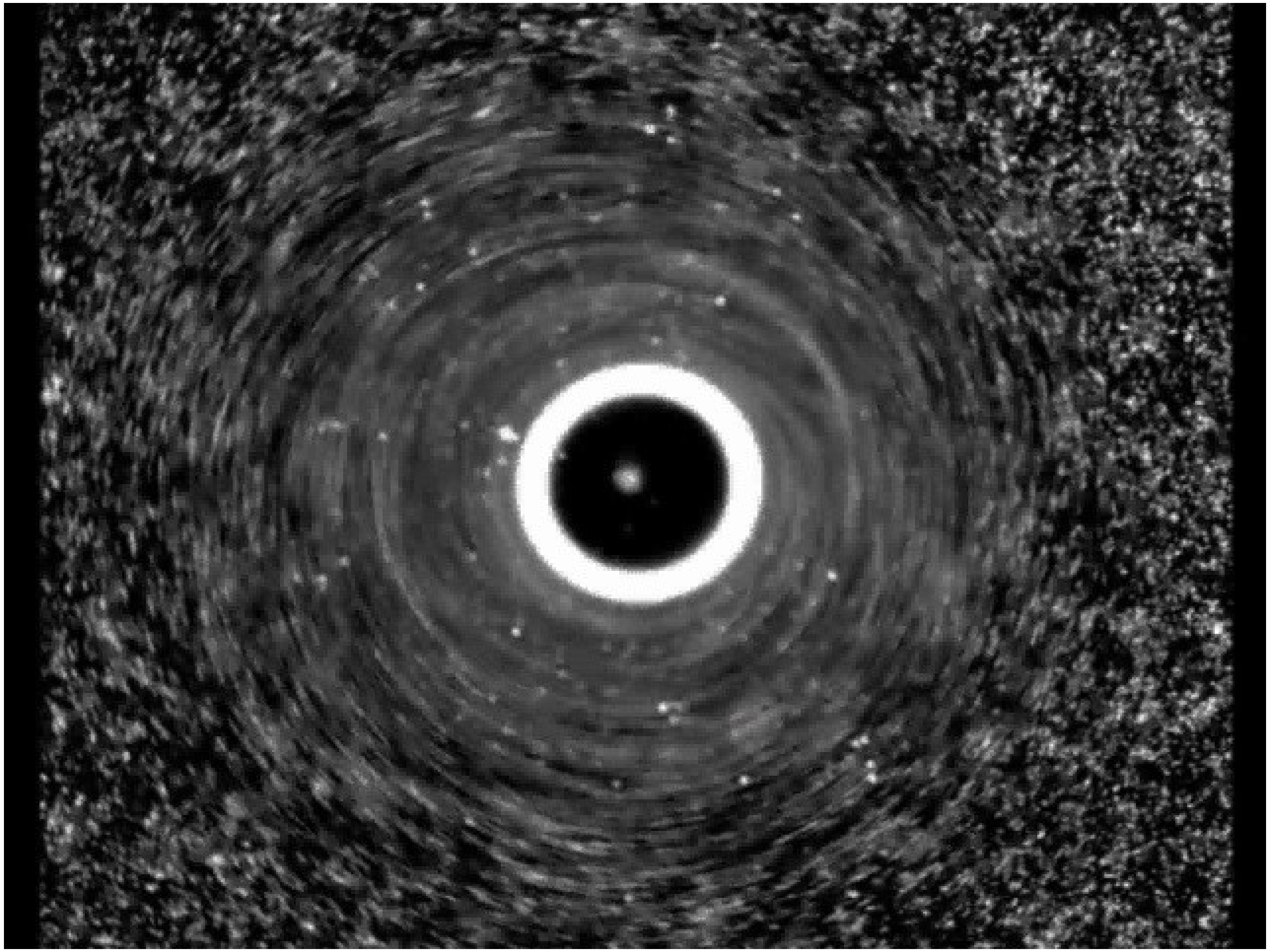
3.2. Acoustic microstreaming patterns



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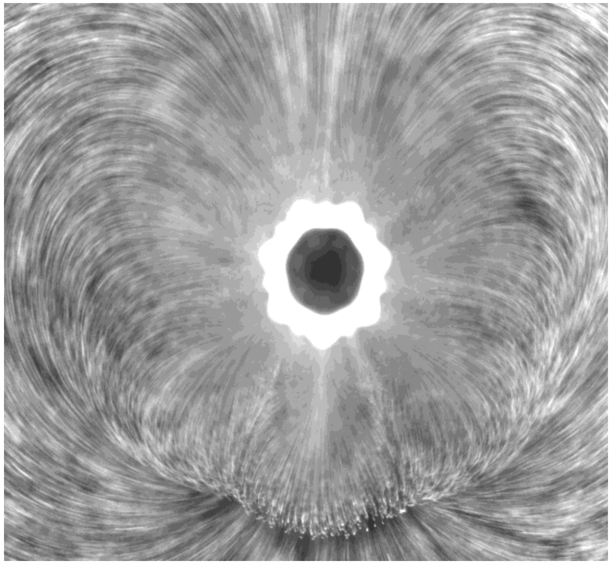
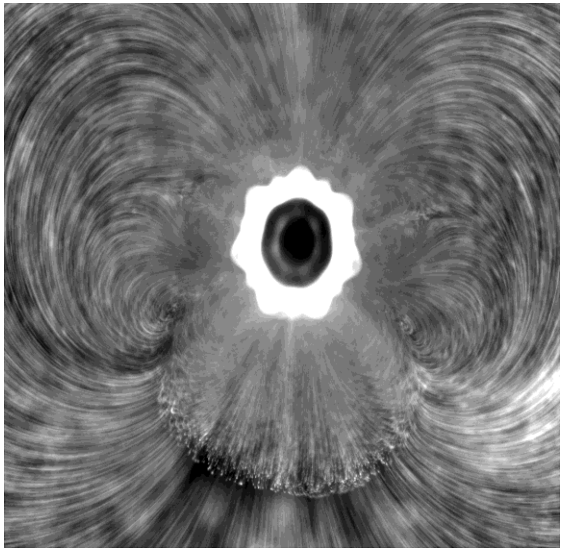
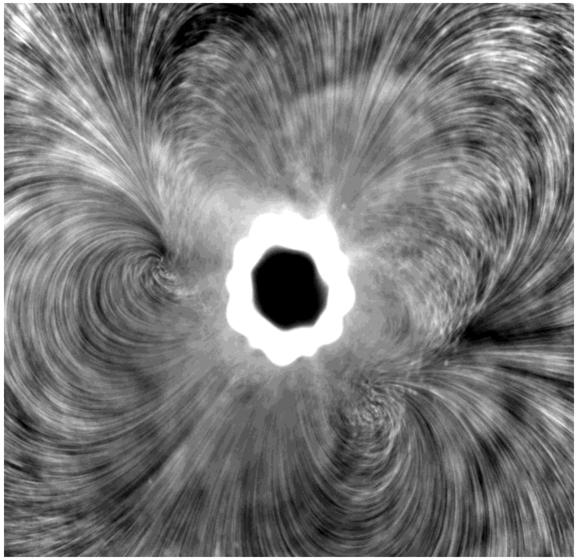
3.2. Acoustic microstreaming patterns

Shape modes







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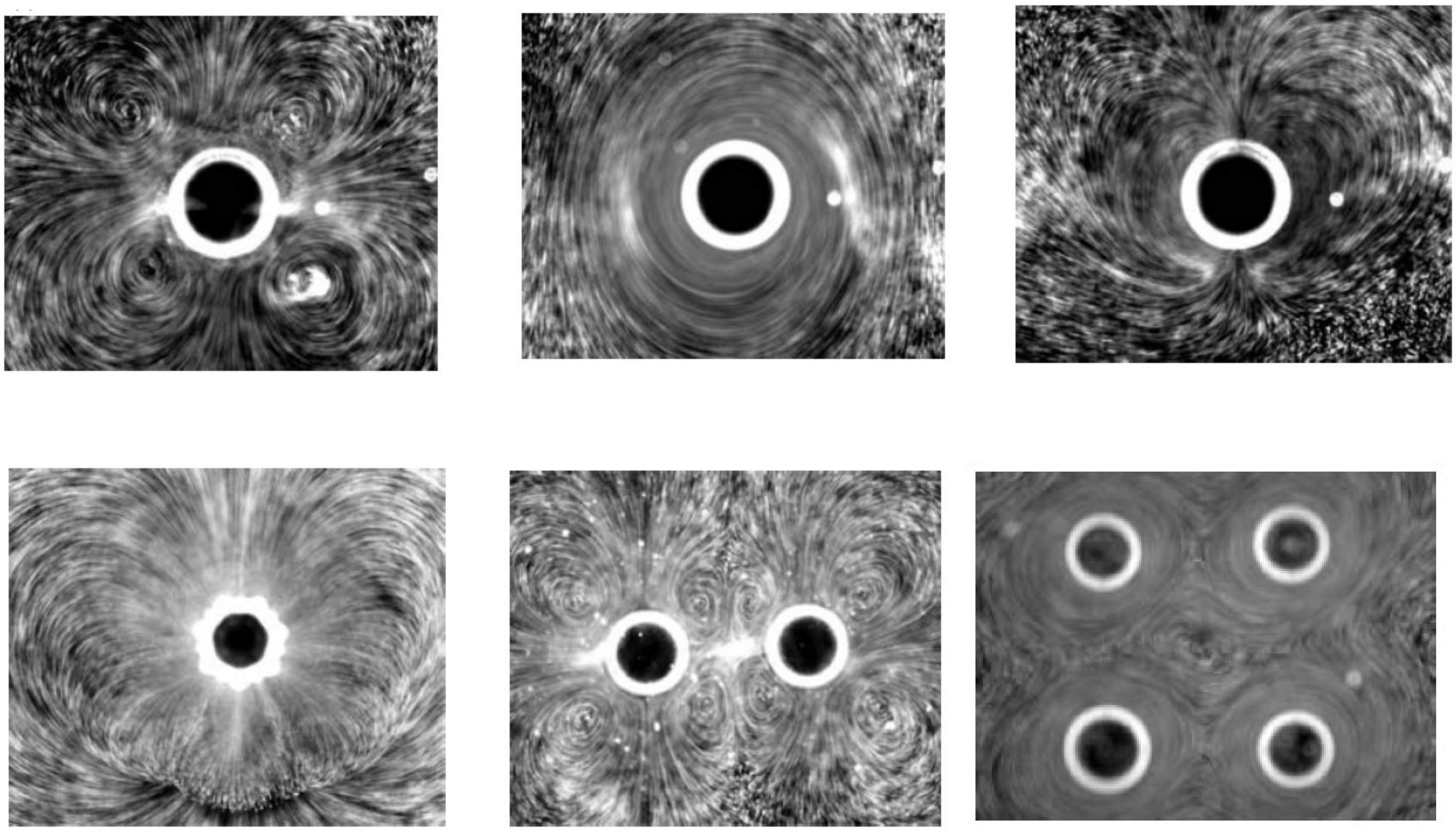
3.2. Acoustic microstreaming patterns

A variety of different flow patterns - streaklines



Tho, P., Manasseh, R., Ooi, A., 2007, *J. Fluid Mech.* 576, 191-233.

4. Microstreaming and micromixing

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The need for chaos

- For molecules to react they must be brought into intimate contact
- Molecular diffusion is extremely slow; rate proportional to $1/L^2$.
- The regions of liquid containing reactants must be blended such that a short distance *L* separates them, permitting fast diffusion
- At macroscopic scales, turbulence rapidly lengthens interfaces, thinning *L*.

- But at microscopic scales, there is no turbulence!
- Liquids must be stirred

Petkovic-Duran, K., et al 2009, *Biotechniques* **47**, 827-833.

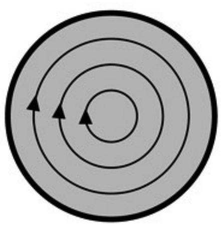
Boon, et al 2011, *Biotechniques* **50**, 116-119.

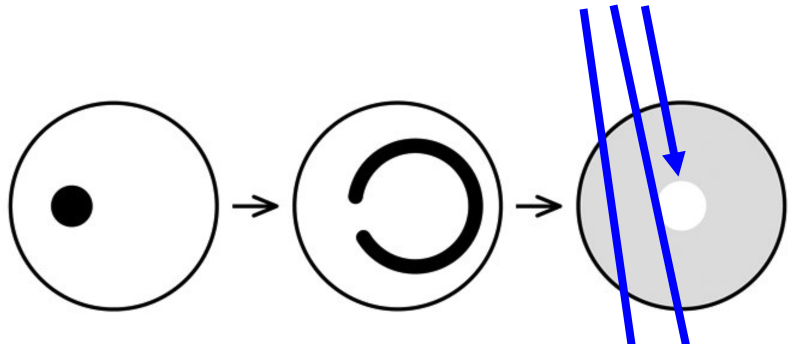
4.1. The micromixing problem

The need for chaos

Stirring steadily with <u>any</u> given pattern
<u>always</u> gives unmixed 'islands'

<u>V</u>ortex





Petkovic-Duran, K., et al 2009, *Biotechniques* **47**, 827-833.

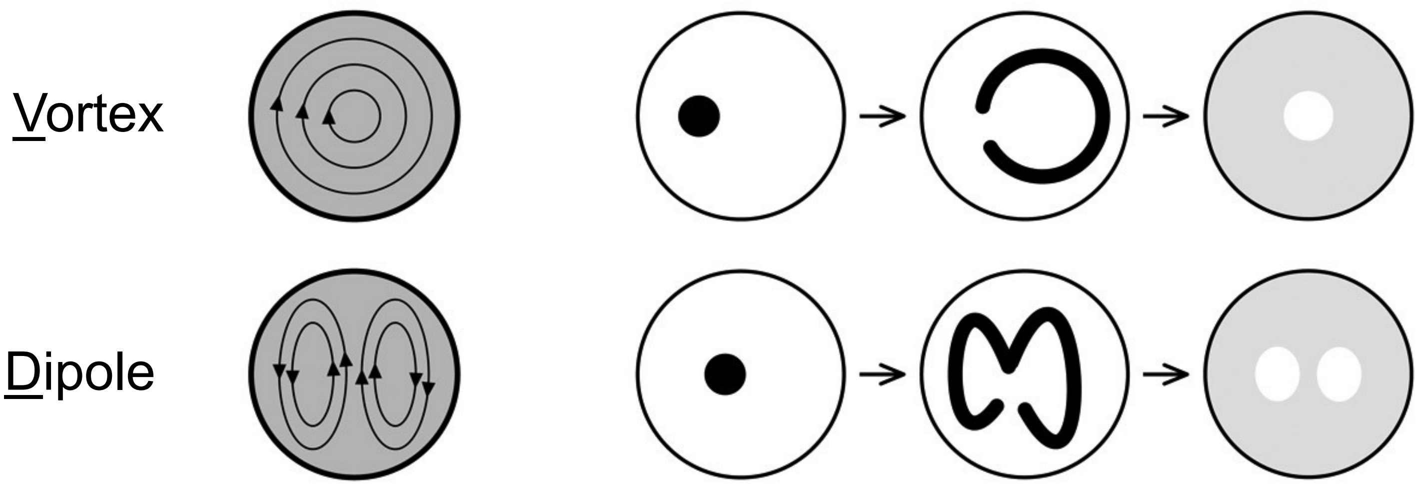
Boon, et al 2011, *Biotechniques* **50**, 116-119.

4.1. The micromixing problem

The need for chaos

Chaotic mixing theory states that to eliminate ‘islands’, patterns must that have mutually intersecting streamlines must be alternated with time:

V → D → V → D → V → D → V → D →

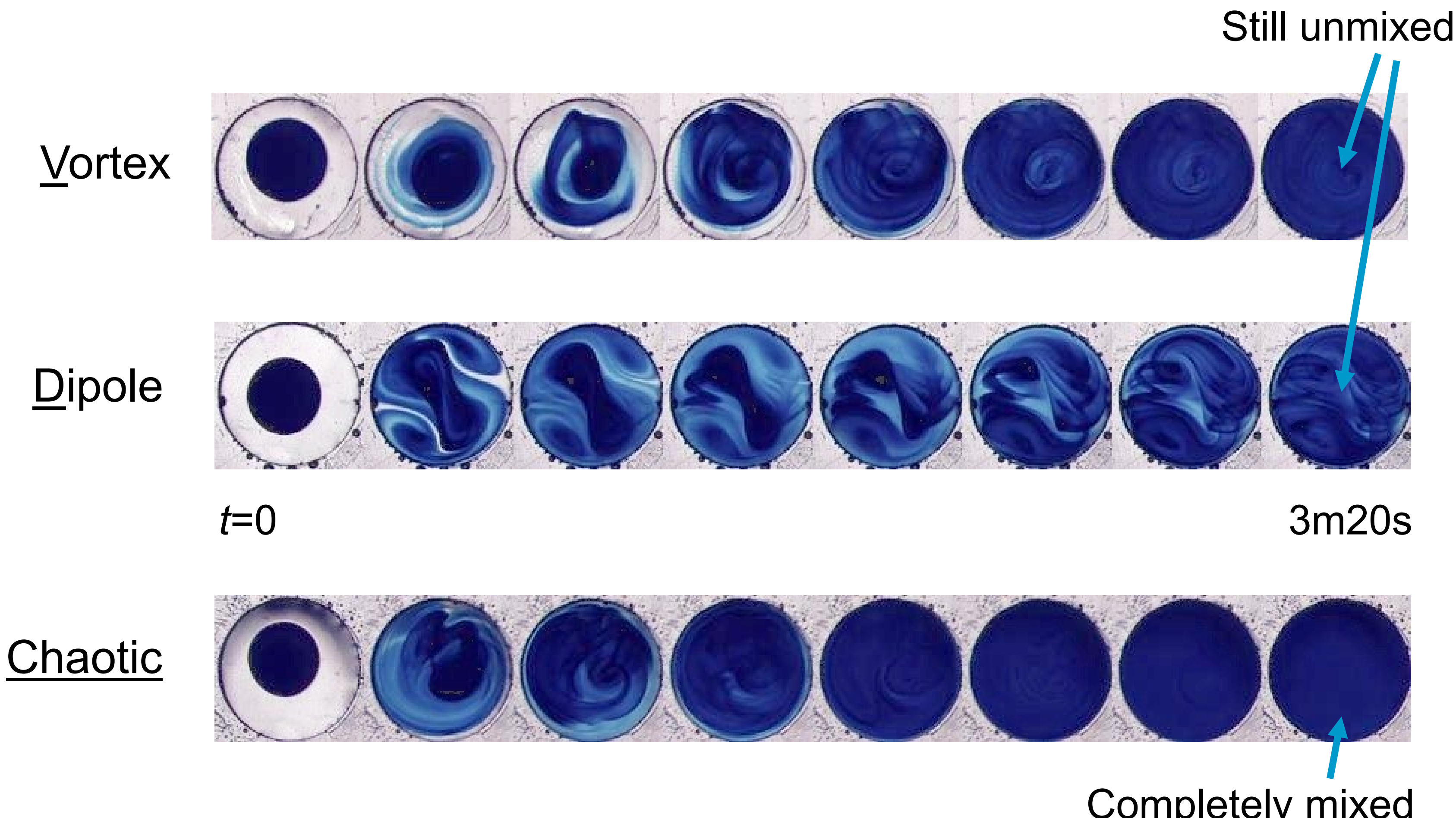


Petkovic-Duran, K., et al 2009, *Biotechniques* **47**, 827-833.

Boon, et al 2011, *Biotechniques* **50**, 116-119.

4.2. Chaotic acoustic micromixing

The need for chaos



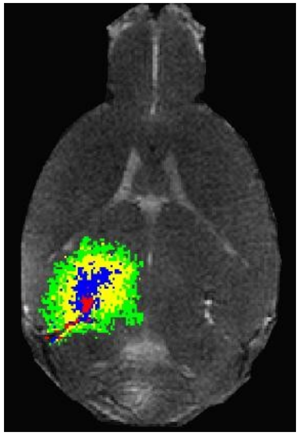
Petkovic-Duran, K., et al 2009, *Biotechniques* **47**, 827-833.
Boon, et al 2011, *Biotechniques* **50**, 116-119.

5. Medical therapeutics with microbubbles

- **Sonoporation** is when molecules (DNA , drugs) that would not normally enter cells are found to enter and deliver **benefit** (gene therapy, chemotherapy) under the action of **ultrasound**

- **Sonothrombolysis** is when dangerous blood clots are dissolved or broken up under the action of **ultrasound**

- Both sonoporation and sonothrombolysis are improved when **microbubbles** are present



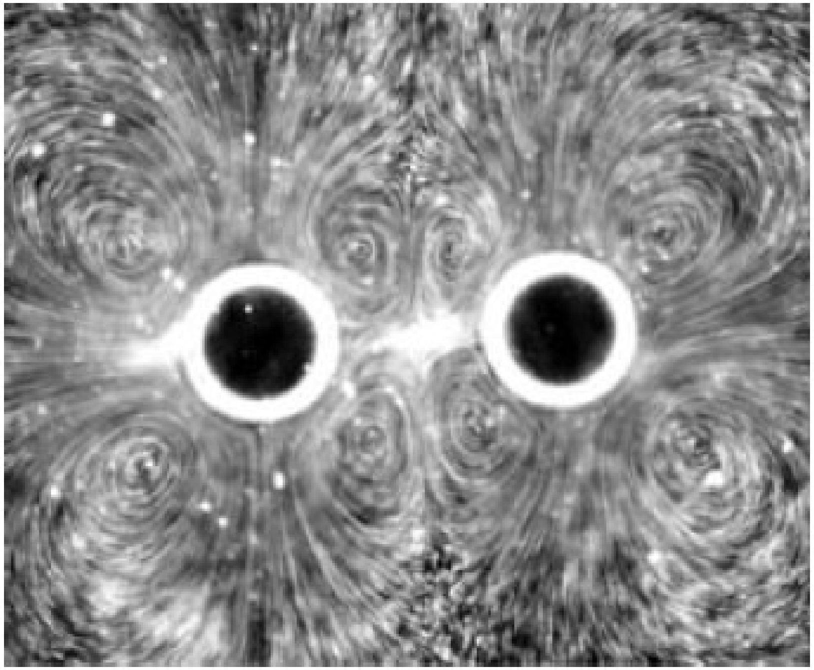
- **Why?**

Collis et al 2010 *Ultrasonics* **50**, 273–279

5.1. Does microstreaming help?

There are *speculations* that ***microstreaming*** around microbubbles creates appropriate stresses on cells, or the extracellular matrix, to cause sonoporation or sonothrombolysis

Perren et al 2008, *J. Thromb Thrombolysis*, **25**, 219-223;
Liu & Wu 2009, *JASA.* **125**, 1319-1330;
Collis et al 2010 *Ultrasonics* **50**, 273–279



Tho et al 2007, *J. Fluid Mech.* **576**, 191-233.

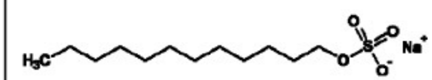
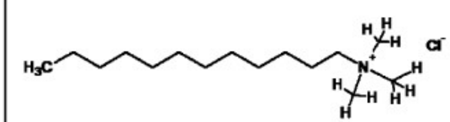
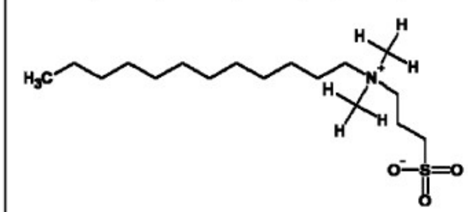
- Can we understand these bioeffects?
- Can we **control** them?

5.2. Surfactants control microstreaming

- Measure microstreaming velocities quantitatively, using microPIV, in the presence of different surfactants: SDS, DTAC, DDAPS

- Surfactant concentrations adjusted to give the **same surface tension**,50+/1 mN/m, irrespective of surfactant type

- Can we affect microstreaming velocities significantly by altering surfactant type?

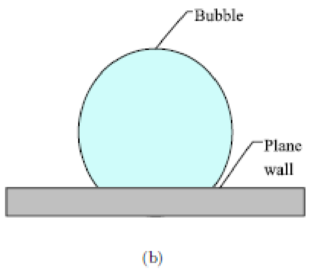
Surfactant	Molecular formula
Sodium dodecyl sulfate (SDS)	$CH_3(CH_2)_{11}SO_4Na$ 
Dodecyl dimethyl ammonium chloride (DTAC)	$CH_3(CH_2)_{11}N(CH_3)_3Cl$ 
Dodecyl dimethyl ammonium propane sulfonate (DDAPS)	$CH_3(CH_2)_{11}N(CH_2)_2(CH_2)_3SO_3$ 

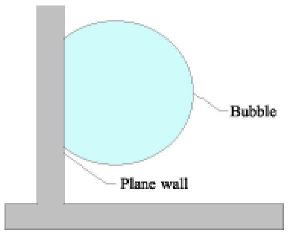
Increasing head-group size

5.2. Surfactants control microstreaming

Bubbles

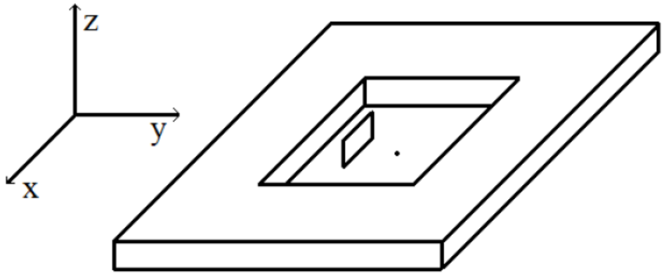
- Single bubbles, pendant (bottom and side)
- Formed by syringe
- 30 – 400 μm in diameter





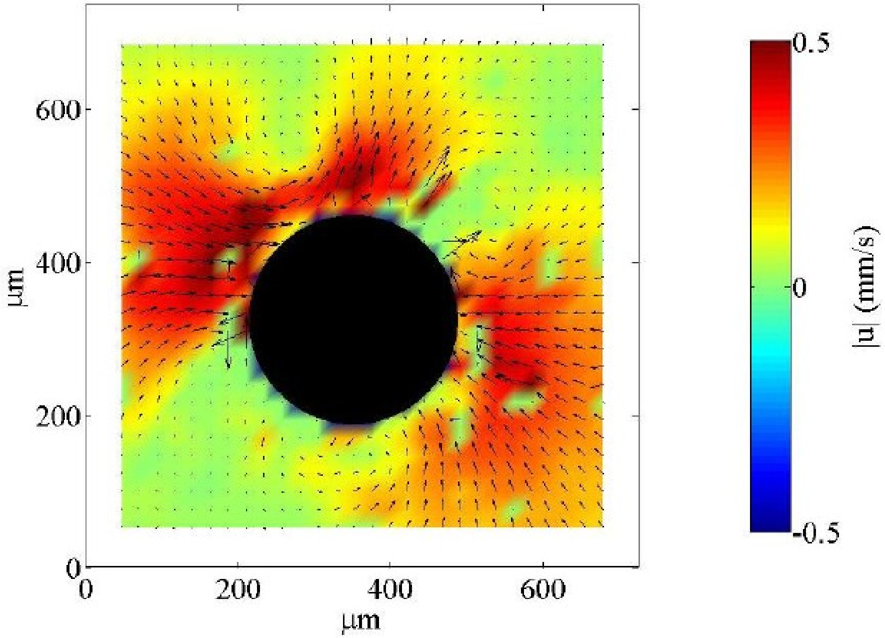
Microchamber & transducer

- 35 mm x 30 mm x (1 or 3) mm
- Additional wall to view bubble side on
- Transducer mounted onto cover
- 28 kHz CW

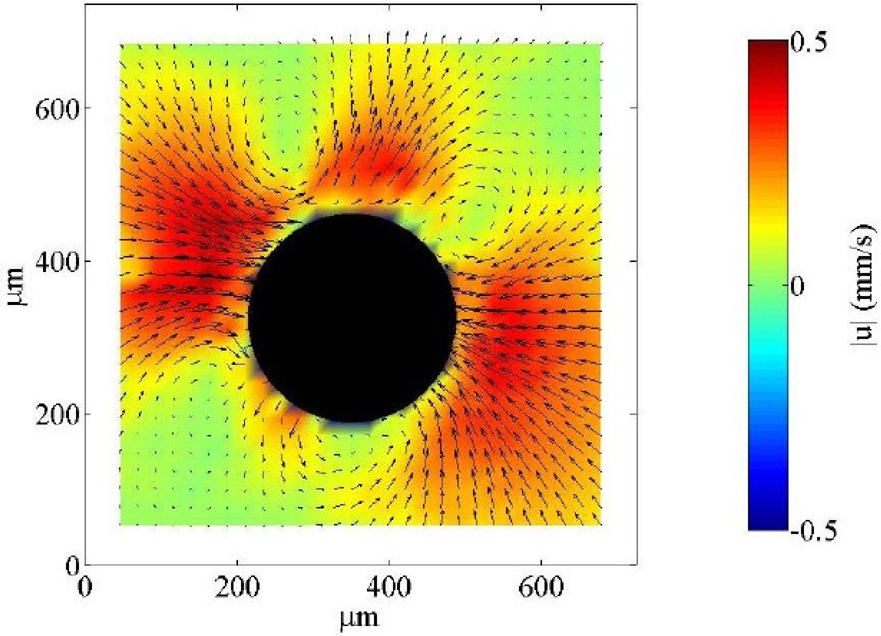


5.2. Surfactants control microstreaming

The PIV image pair were averaged over the data set to remove outliers and anomalies from the PIV analysis (30 – 200 image pairs)



1 image pair



30 image pairs

5.2. Surfactants control microstreaming

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Divergence metric

The **divergence** in the x-y plane measured closest to the wall was calculated

$$\nabla u_{\|w} = \left(\frac{\partial u_{\|}}{\partial x_{\|w}} + \frac{\partial v}{\partial y_{\|w}} \right)$$

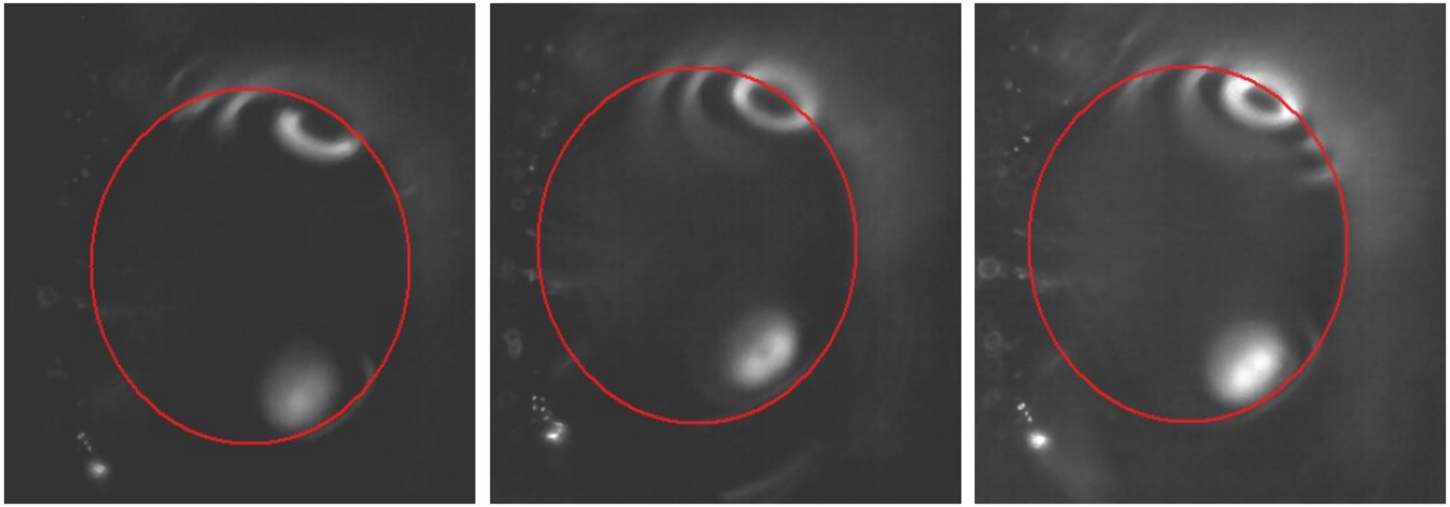
Propose that divergence represents the **stretching or compression** of a cell membrane or tissue surface that the bubble is affecting

The traditional biomedical measure is shear stress, but this is in a plane at right angles to the affected surface

Collis et al 2010 *Ultrasonics* **50**, 273–279

5.2. Surfactants control microstreaming

- Captured on occasions PIV particles adhered to bubble surface
- Velocity = 13 ± 2 mm/s, **two orders of magnitude** greater than secondary velocity

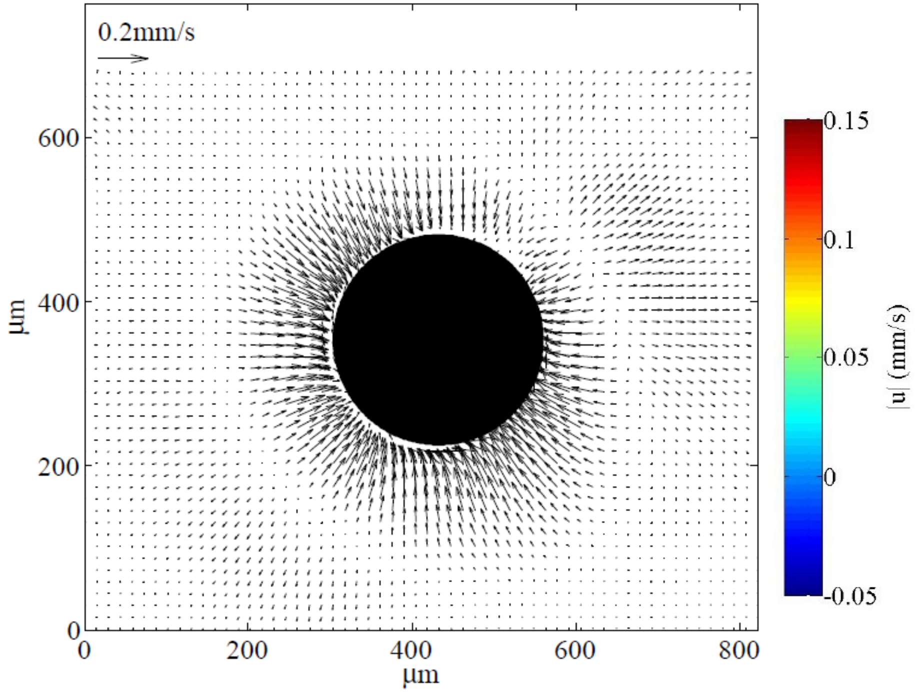


(a) (b) (c)

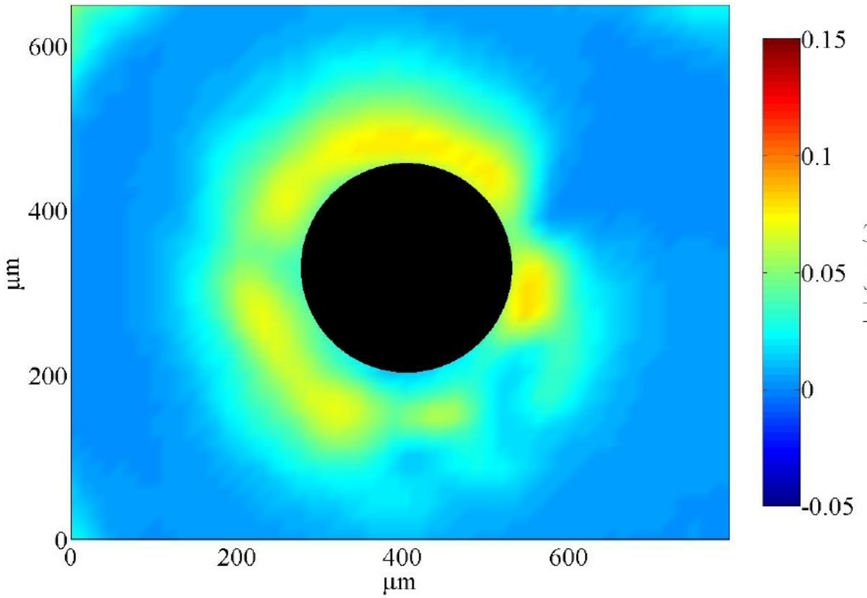
A 270 μm bubble excited at $f = 28$ kHz, amplitude = 20 V_{p-p} and captured in the X-Z plane with varying exposure to estimate the velocity of primary vortices at a speed of 13.35 ± 2 mms^{-1} a) exposure time of 5884 μs, b) exposure time of 8322 μs c) exposure time of 11767 μs

5.2. Surfactants control microstreaming

Surfactant: DDAPS



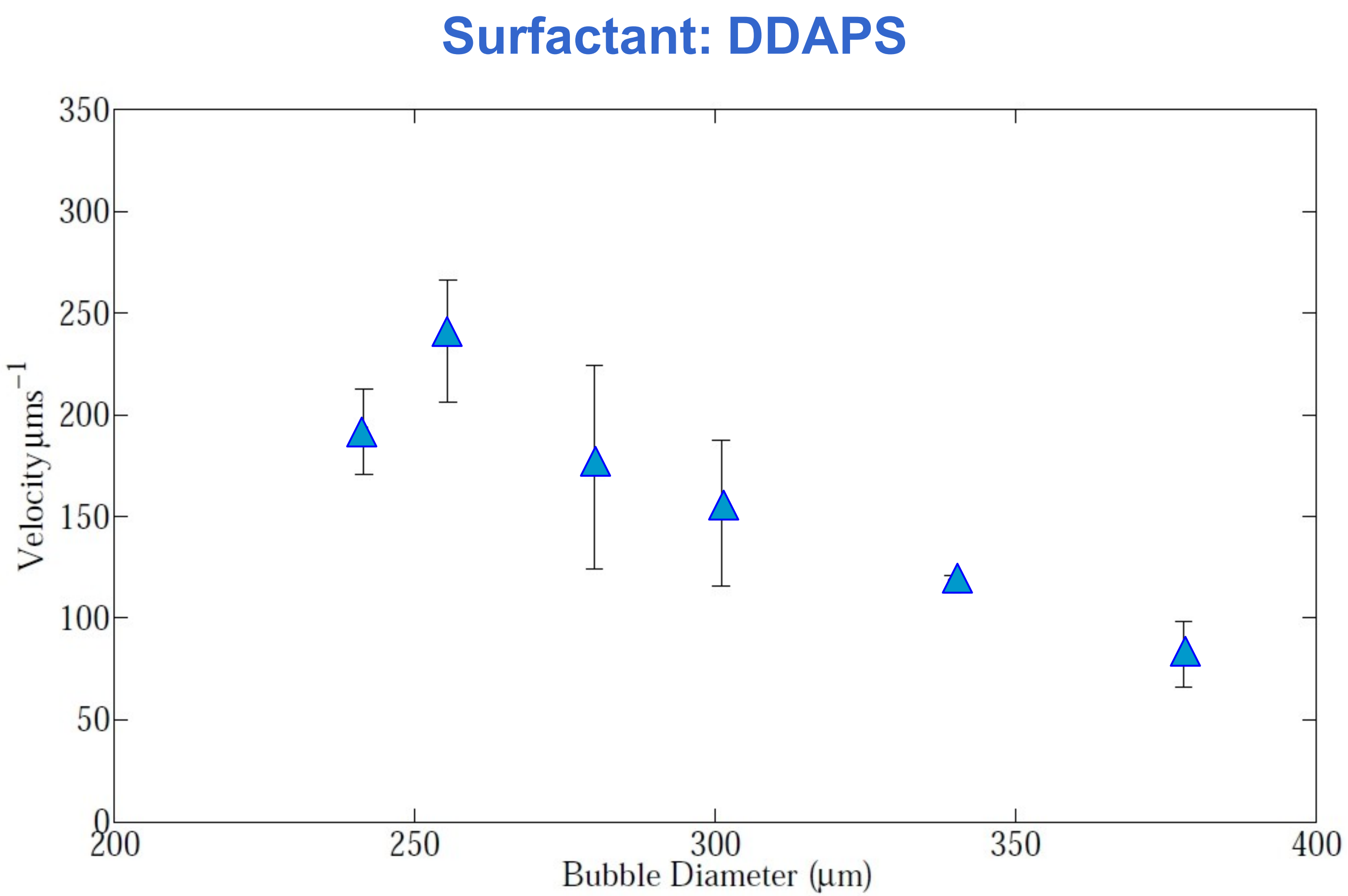
Surfactant: SDS



Velocity magnitude, bubbles driven at 28 kHz, 4.1 kPa

Recall the **surface tension is the same** (within 2%) only the **type of molecule** is different

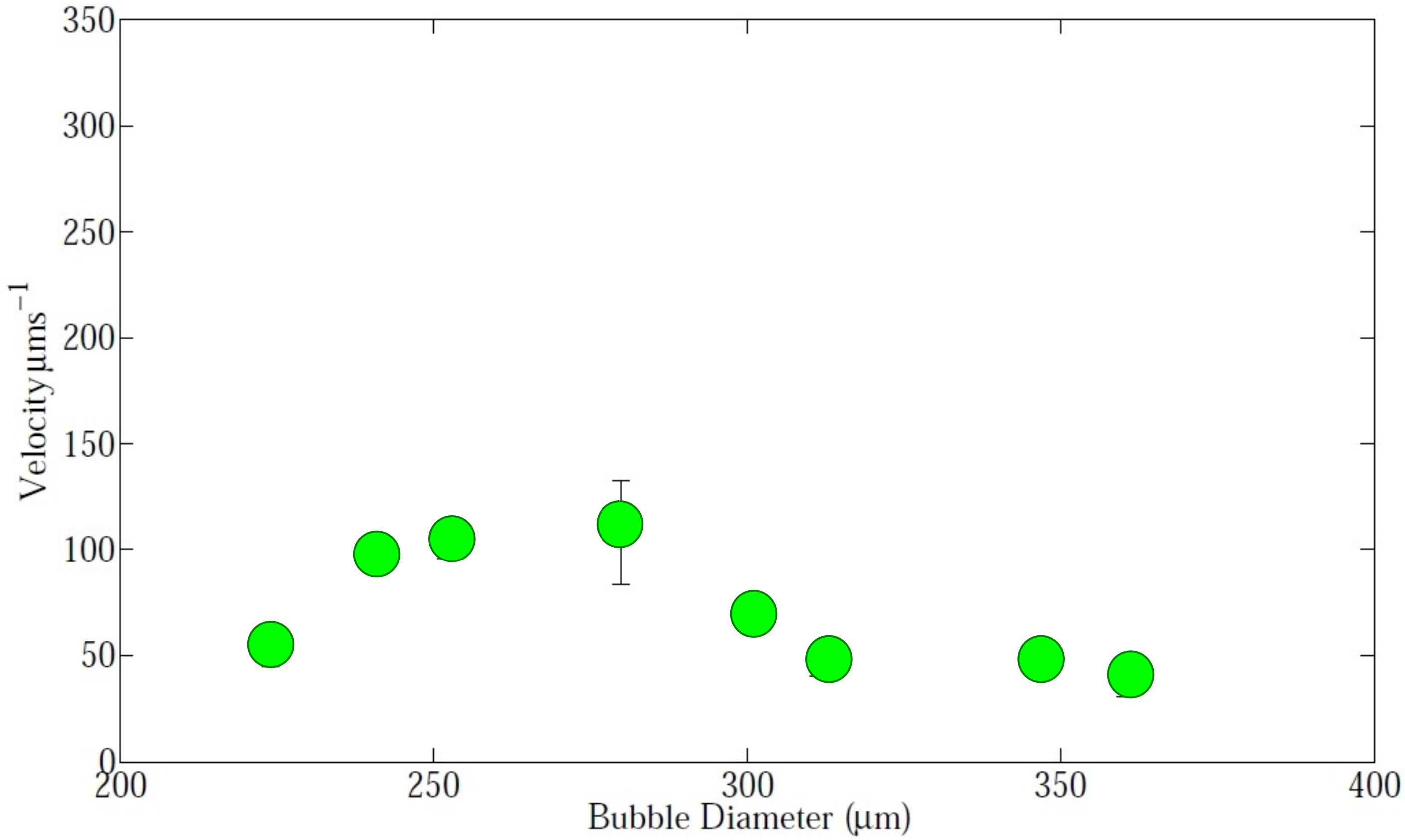
5.2. Surfactants control microstreaming



Maximum microstreaming velocities, bubbles driven at 28 kHz, 4.1 kPa

5.2. Surfactants control microstreaming

Surfactant: SDS



Maximum microstreaming velocities, bubbles driven at 28 kHz, 4.1 kPa

5.2. Surfactants control microstreaming

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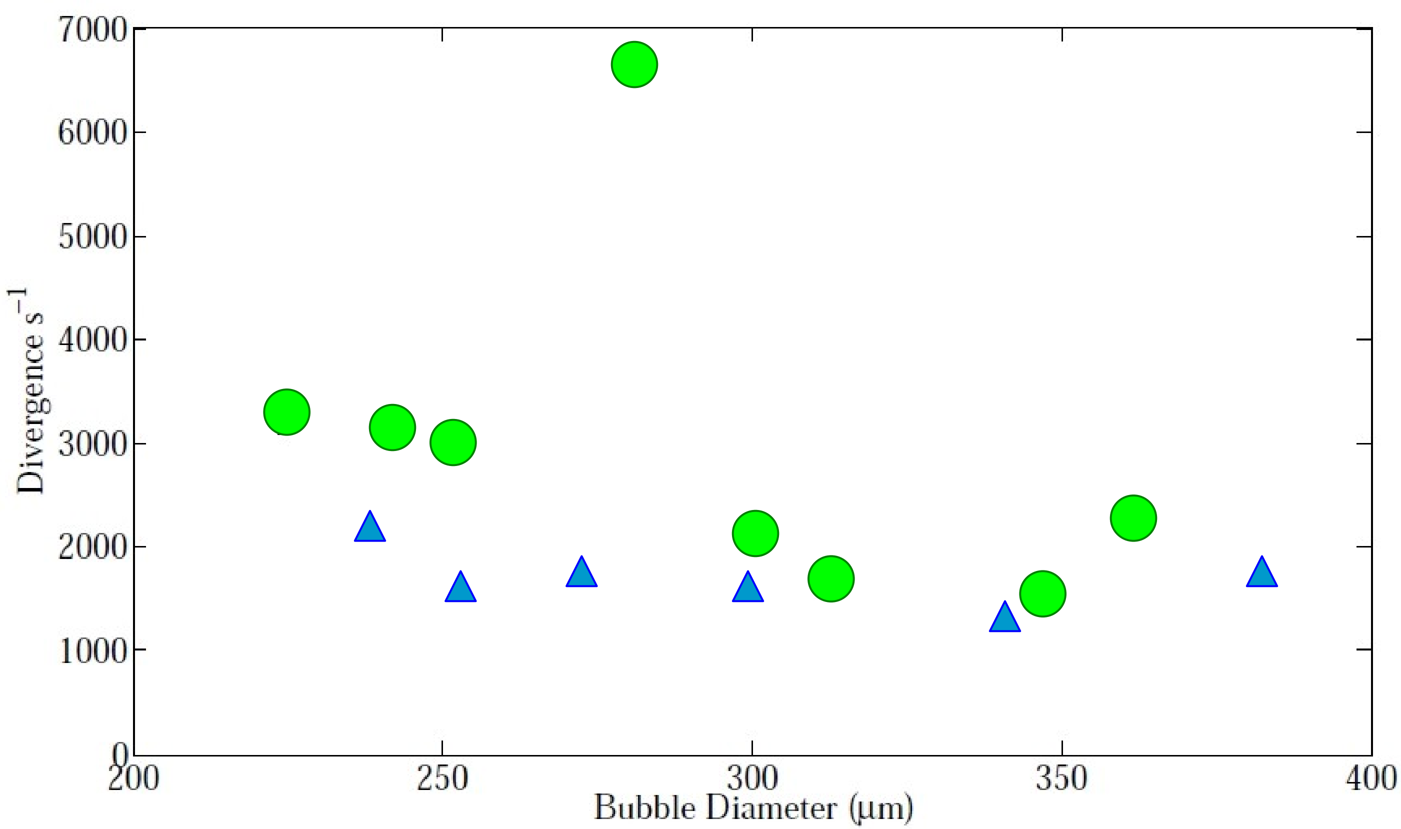
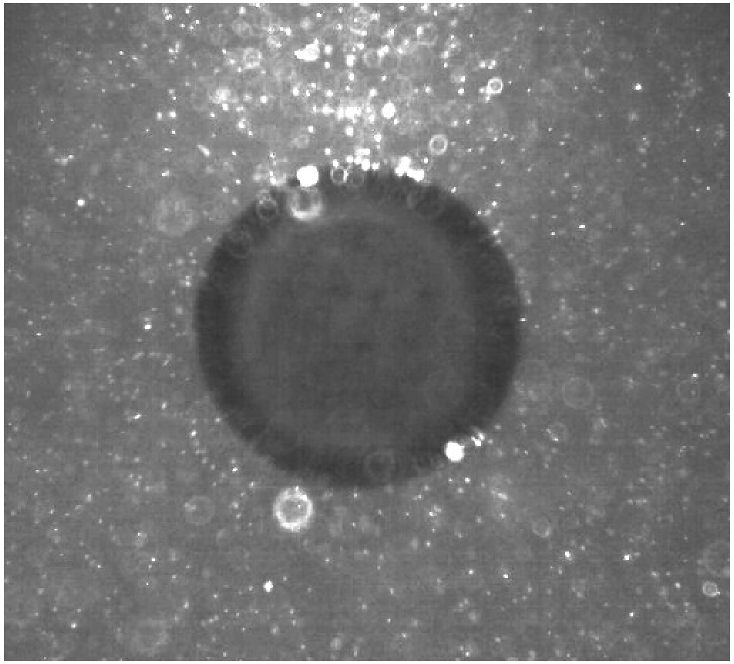
Surfactants: ● **SDS** ▲ **DDAPS**



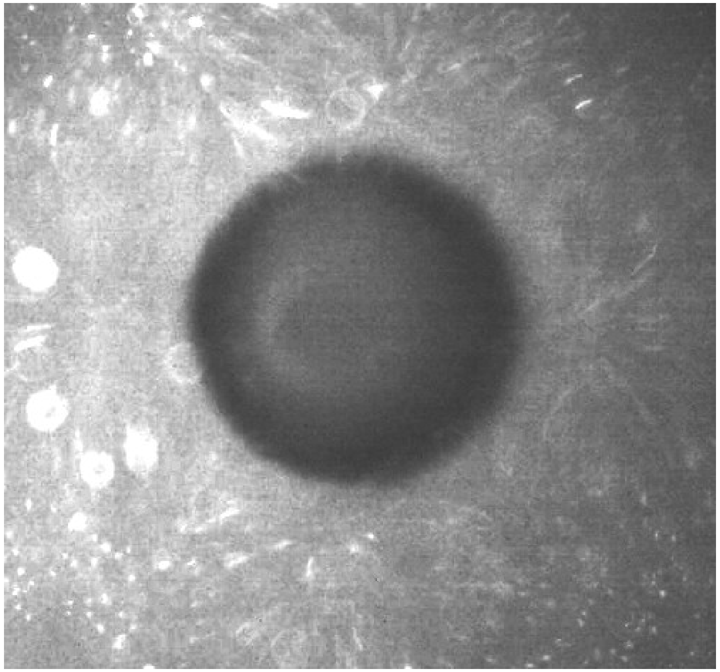
Max Divergence in the *x*-*y* plane, bubbles driven at 28 kHz, 4.1 kPa

5.2. Surfactants control microstreaming

Threshold effect under identical physical and imaging conditions



Water: low velocities



DTAC:
high velocities,surface instabilities

Leong et al 2011, *J. Phys. Chem. C* **115**, 24310

Conclusions

1. Fundamental nonlinearities create steady fluid flows when sound is applied: streaming and microstreaming

2. **Streaming** can be used for medical **diagnostics**

3. **Microstreaming** can occur in a **variety of patterns**

4. **Microstreaming** can be used for **fluid mixing** and may be relevant to new medical **therapeutics**

5. Even when the **surface tension is maintained the same**, surfactants with different molecular head groups create very **different microstreaming velocities**