Lecture 2: Stirring by swimming organisms

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Biomixing

A controversial proposition:

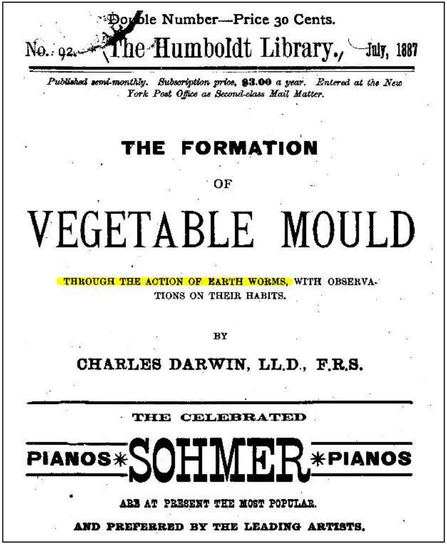
- There are many regions of the ocean that are relatively quiescent, especially in the depths (1 hairdryer/ km^3);
- Yet mixing occurs: nutrients eventually get dredged up to the surface somehow;
- What if organisms swimming through the ocean made a significant contribution to this?
- There could be a local impact, especially with respect to feeding and schooling;
- Also relevant in suspensions of microorganisms (Viscous Stokes regime).

Bioturbation

The earliest case studied of animals ‘stirring’ their environment is the subject of Darwin’s last book.

This was suggested by his uncle and future father-in-law Josiah Wedgwood II, son of the famous potter.

“I was thus led to conclude that all the vegetable mould over the whole country has passed many times through, and will again pass many times through, the intestinal canals of worms.”



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THE FORMATION

OF

VEGETABLE MOULD

THROUGH THE ACTION OF EARTH WORMS, WITH OBSERVATIONS ON THEIR HABITS.

BY

CHARLES DARWIN, LL.D., F.R.S.

THE CELEBRATED

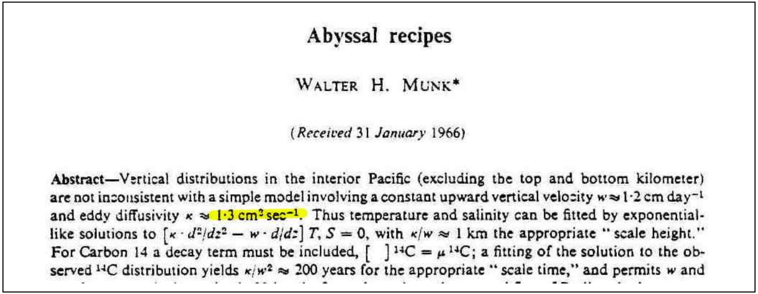
PIANOS * SOHMER * PIANOS

ARE AT PRESENT THE MOST POPULAR

AND PREFERRED BY THE LEADING ARTISTS.

Munk's Idea

Though it had been mentioned earlier, the first to seriously consider the role of ocean biomixing was Walter Munk (1966):



Abyssal recipes

WALTER H. MUNK*

(*Received* 31 *January* 1966)

Abstract—Vertical distributions in the interior Pacific (excluding the top and bottom kilometer) are not inconsistent with a simple model involving a constant upward vertical velocity $w \approx 1{\cdot}2$ cm day^{-1} and eddy diffusivity $\kappa \approx 1{\cdot}3$ cm^2 sec^{-1}. Thus temperature and salinity can be fitted by exponential-like solutions to $[\kappa \cdot d^2/dz^2 - w \cdot d/dz]\, T, S = 0$, with $\kappa/w \approx 1$ km the appropriate "scale height." For Carbon 14 a decay term must be included, $[\quad]\,^{14}\mathrm{C} = \mu\,^{14}\mathrm{C}$; a fitting of the solution to the observed ^{14}C distribution yields $\kappa/w^2 \approx 200$ years for the appropriate "scale time," and permits w and

"…I have attempted, without much success, to interpret [the eddy diffusivity] from a variety of viewpoints: from mixing along the ocean boundaries, from thermodynamic and biological processes, and from internal tides."

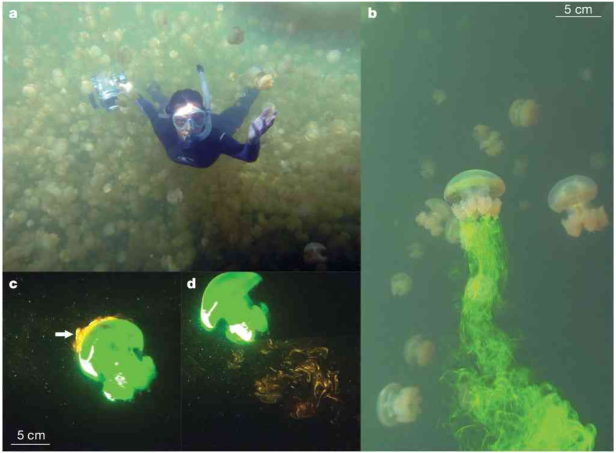
Basic claims

The idea lay dormant for almost 40 years; then

- Huntley & Zhou (2004) analyzed the swimming of 100 (!) species, ranging from bacteria to blue whales. Turbulent energy production is $\sim 10^{-5}\ \mathrm{W\ kg^{-1}}$ for 11 representative species.
- Total is comparable to energy dissipation by major storms.
- Another estimate comes from the solar energy captured: 63 TeraW, something like 1% of which ends up as mechanical energy (Dewar *et al.*, 2006).
- Kunze *et al.* (2006) find that turbulence levels during the day in an inlet were 2 to 3 orders of magnitude greater than at night, due to swimming krill.

In situ experiments

Katija & Dabiri (2009) looked at jellyfish:



[movie 1] (Palau's Jellyfish Lake.)

Displacement by a moving body

86 Mr. J. Clerk-Maxwell *on* [Mar. 10,

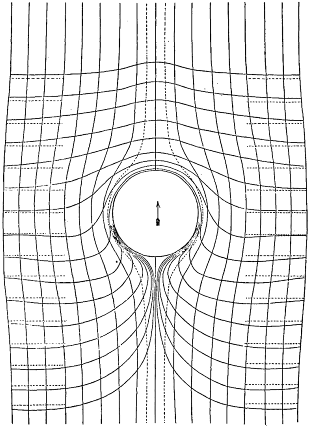


Fig. 1.
Fluid flowing past a fixed cylinder.

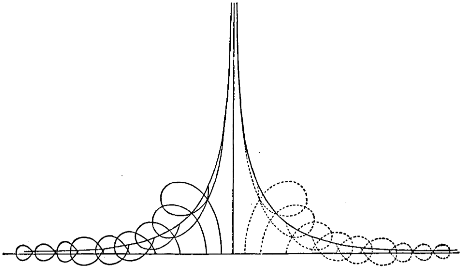
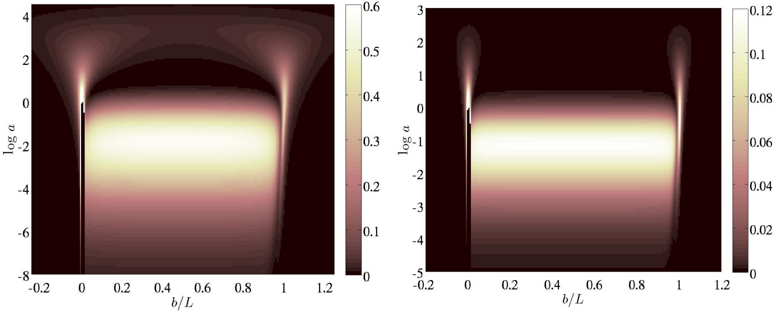


Fig. 2.
Paths of particles of the fluid when a cylinder moves through it.

Maxwell (1869); Darwin (1953); Eames *et al.* (1994); Eames & Bush (1999)

Cylinders and spheres: Displacements



$\Delta_L^2(a,b)\,a$ (cylinder) $\Delta_L^2(a,b)\,a^2$ (sphere)

Displacement for cylinders

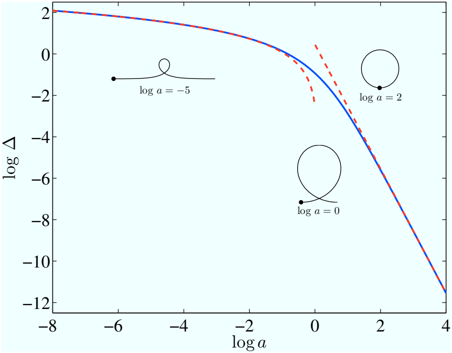
Small a: $\Delta \sim -\log a$

Large a: $\Delta \sim a^{-3}$

(Darwin, 1953)

$\int_0^1 \Delta^2(a)da \simeq 2.31$

$\int_1^\infty \Delta^2(a)da \simeq .06$

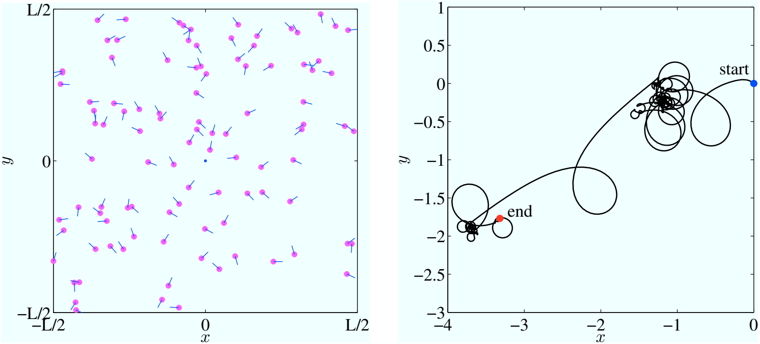


$\Longrightarrow$ 97% dominated by “head-on” collisions (similar for spheres)

Numerical simulation

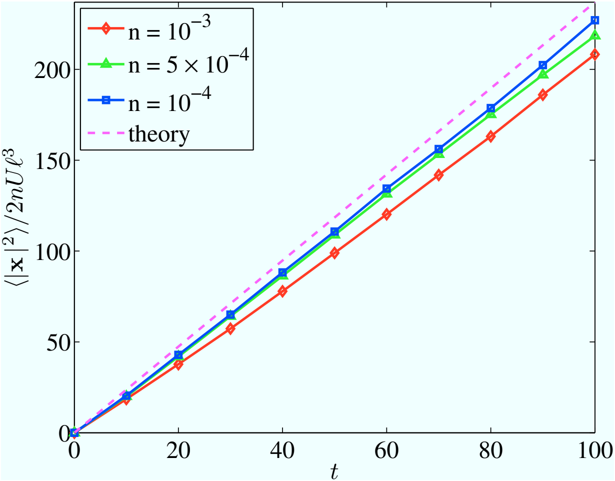
- Validate theory using simple simple simulations;
- Large periodic box;
- N swimmers (cylinders of radius 1), initially at random positions, swimming in random direction with constant speed $U = 1$;
- Target particle initially at origin advected by the swimmers;
- Since dilute, superimpose velocities;
- Integrate for some time, compute $|\mathbf{x}(t)|^2$, repeat for a large number N_{real} of realizations, and average.

A ‘gas’ of swimmers

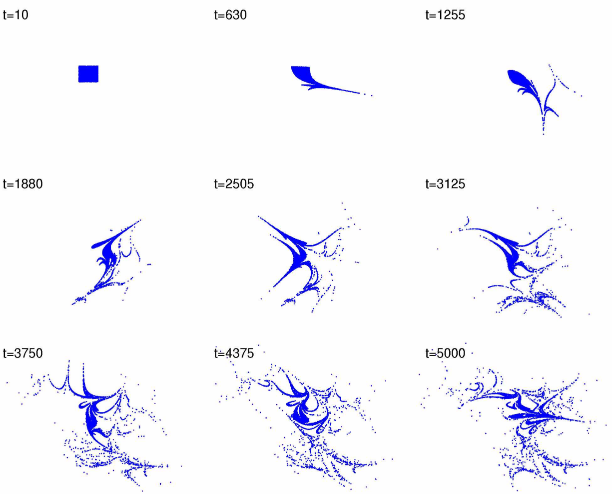


[movie 2] $N = 100$ cylinders, box size $= 1000$

How well does the dilute theory work?

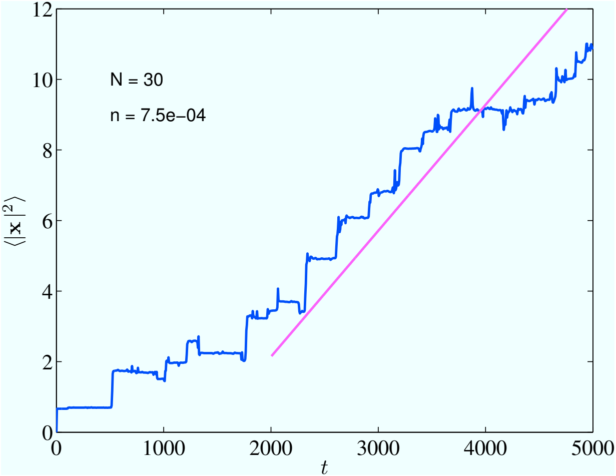


Cloud of particles



[movie 3] (30 cylinders)

Cloud dispersion proceeds by steps

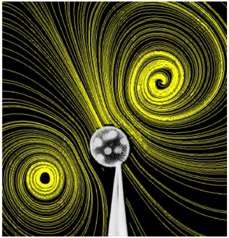


Squirmers

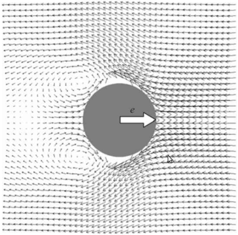
Considerable literature on transport due to microorganisms: Wu & Libchaber (2000); Hernandez-Ortiz *et al.* (2006); Saintillian & Shelley (2007); Underhill *et al.* (2008); Ishikawa (2009); Leptos *et al.* (2009)

Lighthill (1952), Blake (1971), and more recently Ishikawa *et al.* (2006) have considered squirmers:

- Sphere in Stokes flow;
- Steady velocity specified at surface, to mimic cilia;
- Steady swimming condition imposed (no net force on fluid).



(Drescher *et al.*, 2009)



(Ishikawa *et al.*, 2006)

Typical squirmer

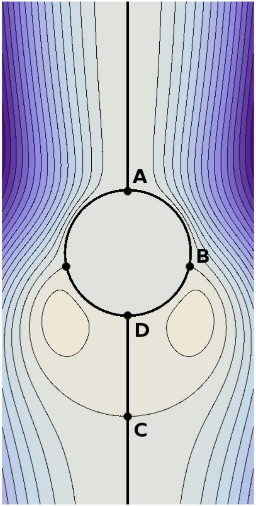
3D axisymmetric streamfunction for a typical squirmer, in cylindrical coordinates (ρ, z):

$$\psi = -\tfrac{1}{2}\rho^2 + \frac{1}{2r^3}\,\rho^2 + \frac{3\beta}{4r^3}\,\rho^2 z\left(\frac{1}{r^2} - 1\right)$$

where $r = \sqrt{\rho^2 + z^2}$, $U = 1$, radius of squirmer $= 1$.

Note that $\beta = 0$ is the sphere in potential flow.

We will use $\beta = 5$ for most of the remainder.

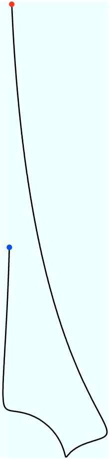


Particle motion for squirmer

A particle near the squirmer’s swimming axis initially (blue) moves towards the squirmer.

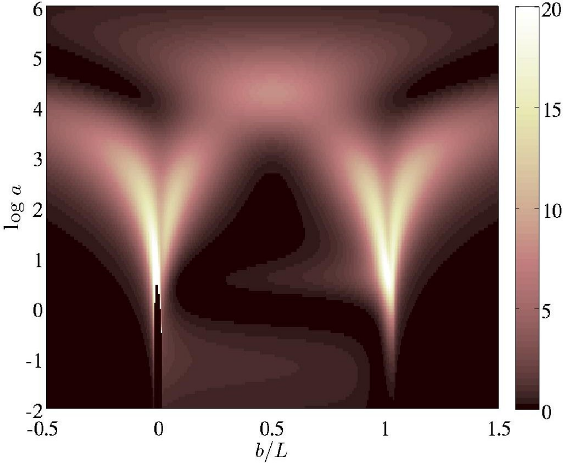
After the squirmer has passed the particle follows in the squirmer’s wake.

(The squirmer moves from bottom to top.)

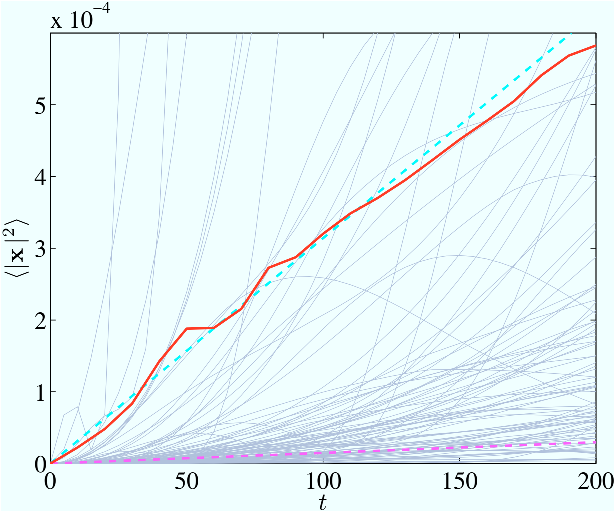


[movie 4]

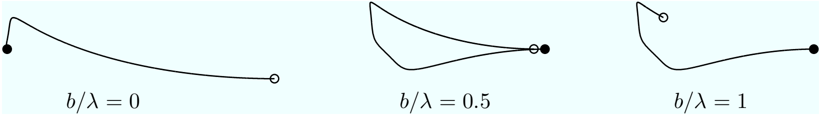
Squirmer displacements



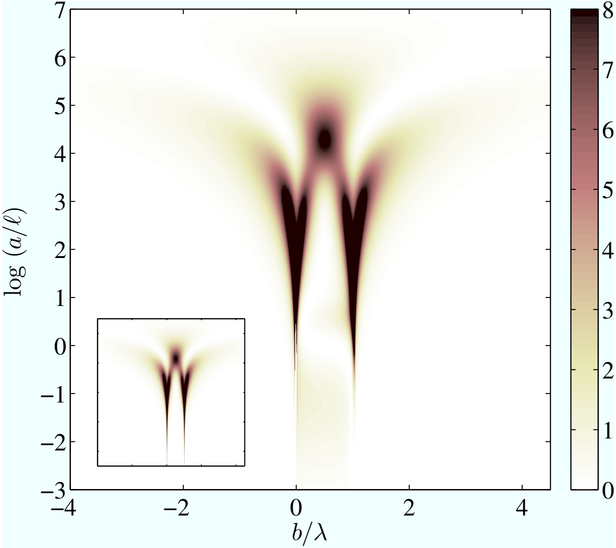
Squirmers: Transport



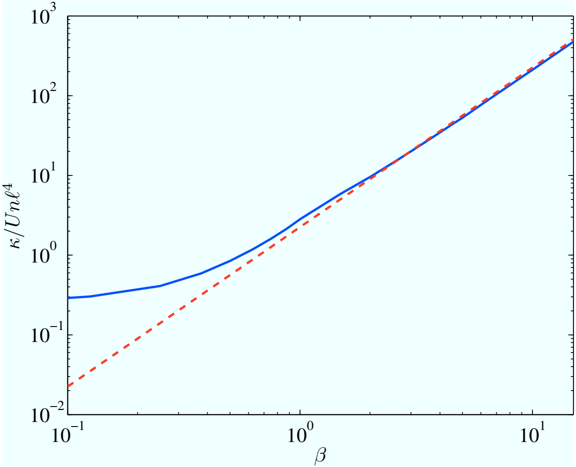
Squirmers: Trajectories



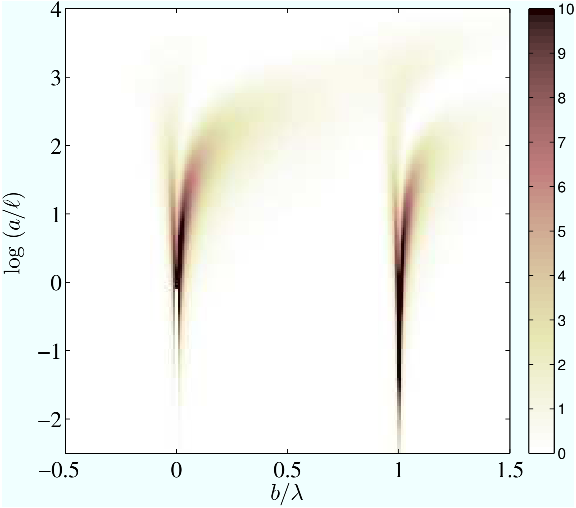
Far field: Displacements



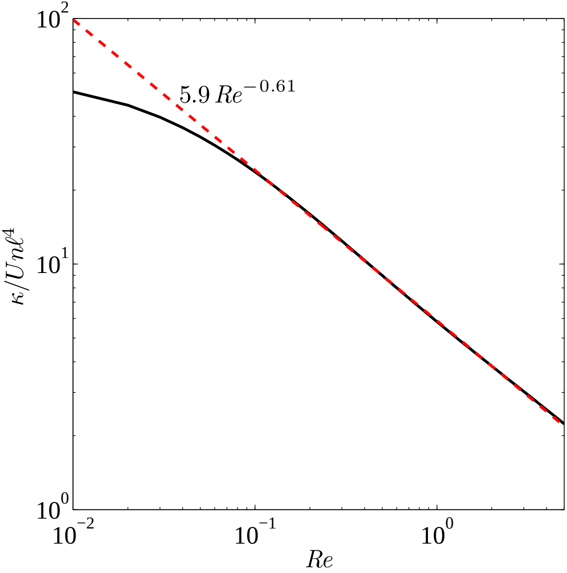
Far field: transport



Finite Reynolds number: Displacements



Finite Reynolds number: Transport



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