# What does the Ashkin-Dziedzic experiment reveal about the electromagnetic force density in matter?

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## Introduction

There are different models for the electromagnetic momentum, stress, and force density inside a material (see Table 1). Some experiments have taken steps towards resolving their validity.

- The 1973 experiment by Ashkin and Dziedzic [1] showed that pulses directed onto an air-water interface caused it to bulge towards air (the lower index region) regardless of the illumination direction.
- A similar experiement by Casner et al. [2] showed that a beam directed onto a fluid-fluid interface caused it to bulge downwards, also towards the lower index region.

These observation suggest the Minkowski form but this has not been firmly established [3, 4].

We study radiation pressure on a fluid interface using a coupled electromagnetic and fluid dynamic simulator that solves Maxwell's equations, electromagnetic momentum continuity, and the Navier Stokes equation. Force densities of Abraham, Minkowski, and Einstein-Laub all predict fluid deformations consistent with experiment. Force densities of Amperian and Chu however, predict polarization-dependent deformation inconsistant with experiments.

## Methodology

Maxwell's equations are solved using FDTD. The force density is calculated from momentum continuity given the stess tensor $\bar{\bar{T}}$ and momentum density $\vec{G}$ from the postulate sets listed in Table 1. Fluid deformation is modelled using the Navier Stokes equation.

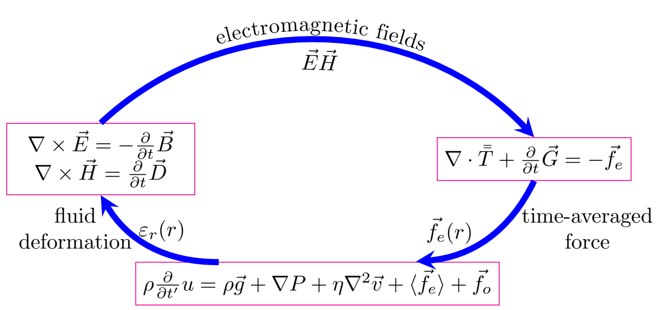


**Figure 1.** Simulation framework used to study radiation pressure in fluid media. Because $t << t'$, the time-averaged (as oppossed to instantaneous) force density is used to calculate fluid deformation.

| Form | $\vec{G}$ | $\vec{S}$ | $\bar{\bar{T}}$ |
|---|---|---|---|
| Minkowski | $\vec{D}\times\vec{B}$ | $c^2\vec{D}\times\vec{B}$ | $(\vec{D}\cdot\vec{E}+\vec{B}\cdot\vec{H})\bar{\bar{I}}/2-\vec{D}\vec{E}-\vec{B}\vec{H}$ |
| Abraham | $\vec{E}\times\vec{H}/c^2$ | $\vec{E}\times\vec{H}$ | $(\vec{D}\cdot\vec{E}+\vec{B}\cdot\vec{H})\bar{\bar{I}}/2-\vec{D}\vec{E}-\vec{B}\vec{H}$ |
| Einstein-Laub | $\vec{E}\times\vec{H}/c^2$ | $\vec{E}\times\vec{H}$ | $(\varepsilon_o\vec{E}^2+\mu_o\vec{H}^2)\bar{\bar{I}}/2-\vec{D}\vec{E}-\vec{B}\vec{H}$ |
| Amperian | $\varepsilon_o\vec{E}\times\vec{B}$ | $\vec{E}\times\vec{B}/\mu_o$ | $(\varepsilon_o\vec{E}^2+\mu_o^{-1}\vec{B}^2)\bar{\bar{I}}/2-\varepsilon_o\vec{E}\vec{E}-\mu_o^{-1}\vec{B}\vec{B}$ |
| Chu | $\vec{E}\times\vec{H}/c^2$ | $\vec{E}\times\vec{H}$ | $(\varepsilon_o\vec{E}^2+\mu_o\vec{H}^2)\bar{\bar{I}}/2-\varepsilon_o\vec{E}\vec{E}-\mu_o\vec{H}\vec{H}$ |

**Table 1.** Five formulations of electrodynamics used here to model radiation pressure on fluid interfaces.

## Results

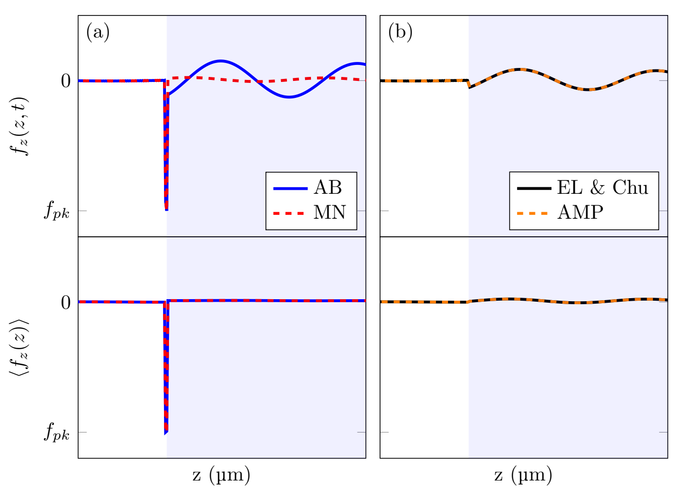


**Figure 3.** Degeneracy of the time-averaged force densities predicted by different formulation of electrodynamics. Here we compare the (top row) instantaneous and (bottom row) time-averaged force densities for the case of monochromatic wave of 500 nm wavelength incident from air into water.

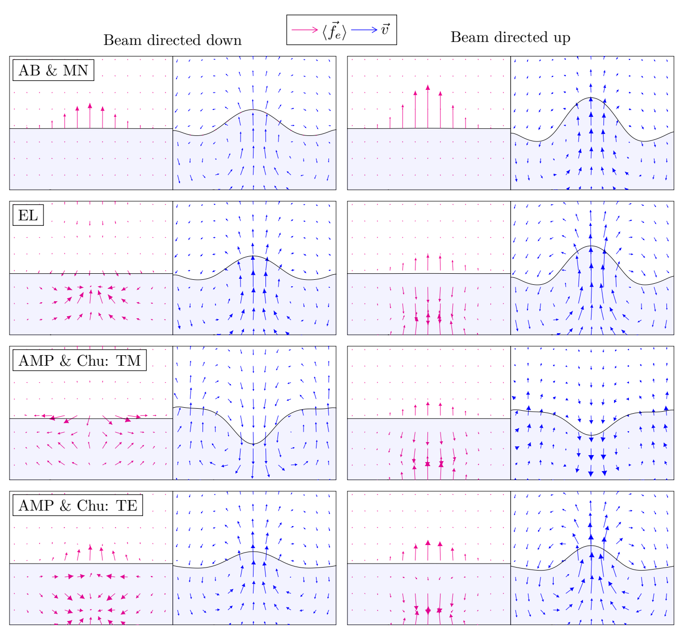


**Figure 2.** Simulation of the Ashkin-Dziedzic experiment using five electrodynamic models for illumination from above and below. (magenta arrows) depict time-averaged force density and the (blue-arrows) depict the velocity field of the fluid.

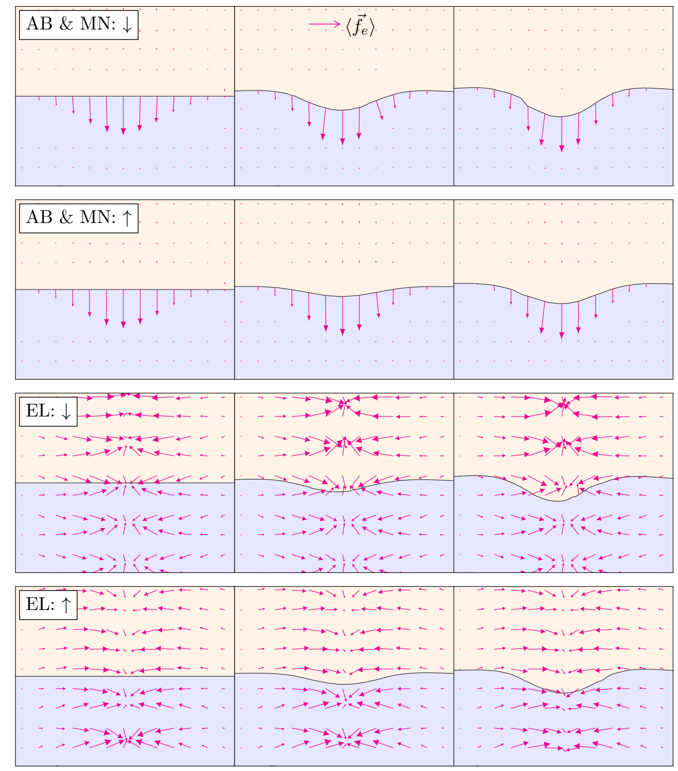


**Figure 4.** Simulation of the Casner et al. experiment using the three models validated in Figure 2. Magenta arrows depict time-averaged force density.

## Conclusions

- Radiation pressure on fluid interfaces cannot distinguish betweeen Abraham and Minkowski models.
- The Abraham, Minkowski, and Einstein-Laub models all correctly describe observations, but present different mechanisms for bulge formation. The first two rely interface forces, the latter relies on body forces.
- The Amperian and Chu models are inconsistent with experiments.

## References

[1] Ashkin A and Dziedzic J M. Radiation Pressure on a Free Liquid Surface. *Phys. Rev. Lett.*, 30:139–142, 1973.

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[3] Kemp B A. Resolution of the Abraham-Minkowski debate: Implications for the electromagnetic wave theory of light in matter. *J. Appl. Phys.*, 109:111101, 2011.

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