Asymmetric drop coalescence launches fungal ballistospores with directionality: Supplementary material

S.1 Nomenclature

Symbols

E	Energy
$\boldsymbol{f}$	Force
g	Gravitational acceleration
G	Chemical potential
l	Diffusion length
m	Mass
$\boldsymbol{n}$	Unit normal
P	Pressure
r	Radius
t	Time
u	Tangential velocity
v	Normal velocity
$\boldsymbol{V}$	Velocity
β	Positioning angle
γ	Mobility parameter
ϵ	Capillary width
θ	Young's contact angle
λ	Interfacial energy density
μ	Viscosity
ρ	Density
σ	Surface tension
Φ	Phase-field variable
ψ	Cap angle
$\boldsymbol{\wp}$	Liquid momentum
Δ	Change (in surface energy)
$\boldsymbol{\nabla}$	Gradient operator

Subscripts

$_A$	Adaxial drop
$_B$	Buller's drop
$_{ci}$	Capillary-inertial
$_d$	Diffusion
$_G$	Gas
$_k$	Translational kinetic energy
$_L$	Liquid
$_N$	Normal direction (perpendicular to the adaxial plane)
$_S$	Spore
$_{SL}$	Spore-liquid complex
$_T$	Tangential direction (parallel to the adaxial plane)

Superscripts

*	Nondimensional quantity
$\hat{}$	Evaluated at $\hat{t}$, the point of peak tangential momentum

Nondimensional Variables

$\boldsymbol{f}^*$	Force, $\boldsymbol{f}^* = \boldsymbol{f}/(\sigma r_B)$
f_N^*	Normal force, $f_N^* = f_N/(\sigma r_B)$

f_T^* Tangential force, $f_T^* = f_T/(\sigma r_B)$
m^* Mass ratio, $m^* = m_B/(m_S + m_L)$, where the liquid mass $m_L = m_A + m_B$
Oh Ohnesorge number, $Oh = \mu_L/\sqrt{\rho_L \sigma r_B}$
P^* Pressure, $P^* = P(r_B/\sigma)$
t^* Time, $t^* = t/t_{ci}$, where $t_{ci} = \sqrt{\rho_L r_B^3/\sigma}$
$\hat{t}^*$ Point of departure, i.e. point of peak tangential momentum, $\hat{t}^* = \hat{t}/t_{ci}$
$\boldsymbol{V}^*$ Velocity, $\boldsymbol{V}^* = \boldsymbol{V}/u_{ci}$, where $u_{ci} = \sqrt{\sigma/(\rho_L r_B)}$
u_L^* Tangential velocity averaged over the liquid mass, $u_L^* = u_L/u_{ci}$
$\hat{u}_L^*$ Tangential liquid velocity at the point of departure $\hat{t}^*$, $\hat{u}_L^* = \hat{u}_L/u_{ci}$
u_{SL}^* Tangential velocity of the spore-liquid complex, $u_{SL}^* = u_{SL}/u_{ci}$
v_L^* Normal velocity averaged over the liquid mass, $v_L^* = v_L/u_{ci}$
$\hat{v}_L^*$ Normal liquid velocity at the point of departure $\hat{t}^*$, $\hat{v}_L^* = \hat{v}_L/u_{ci}$
v_{SL}^* Normal velocity of the spore-liquid complex, $v_{SL}^* = v_{SL}/u_{ci}$
γ^* Mobility, $\gamma^* = \gamma\sqrt{\rho\sigma/r_B^3}$
ϵ^* Capillary width, $\epsilon^* = \epsilon/r_B$
$\boldsymbol{\wp}^*$ Momentum, $\boldsymbol{\wp}^* = \boldsymbol{\wp}/(m_B u_{ci})$
$\wp_N^*$ Normal momentum, $\wp_N^* = \wp_N/(m_B u_{ci})$
$\hat{\wp}_N^*$ Normal momentum at $\hat{t}^*$, $\hat{\wp}_N^* = \hat{\wp}_N/(m_B u_{ci})$
$\wp_T^*$ Tangential momentum, $\wp_T^* = \wp_T/(m_B u_{ci})$
$\hat{\wp}_T^*$ Tangential momentum at $\hat{t}^*$, $\hat{\wp}_T^* = \hat{\wp}_T/(m_B u_{ci})$
$\boldsymbol{\nabla}^*$ Gradient operator, $\boldsymbol{\nabla}^* = r_B \boldsymbol{\nabla}$

Note: All parameters are nondimensionalized by the density (ρ_L), surface tension (σ) and radius (r_B) of the Buller's drop, except for $\boldsymbol{\wp}^*$ and m^*. The nondimensional momentum ($\boldsymbol{\wp}^*$) normalizes the liquid momentum $\boldsymbol{\wp} = m_L \boldsymbol{V}_L$ with the Buller's drop mass ($m_B = \frac{4}{3}\pi\rho_L r_B^3$ in 3D simulations) and the capillary-inertial velocity, $u_{ci} = \sqrt{\sigma/(\rho_L r_B)}$. The mass ratio ($m^*$) is between the Buller's drops mass (m_B) and the combined spore-liquid mass ($m_{SL} = m_S + m_A + m_B$).

S.2 Experimental Methods

For the experimental demonstration in figure 3, the spore-shaped particle is a spherical cap razor-cut from a polystyrene sphere (Norstone 0.4mm SHC) with a density of 1050 kg/m^3. The polystyrene cap is rendered hydrophilic after a treatment with oxygen plasma (Emitech K-1050X). The hydrophilic model particle is placed on a superhydrophobic substrate made of copper oxide nanostructures [27] and coated with trichlorosilane (Acros 10655002). The spore orientation is controlled by tweezers, assisted by gentle shaking of the substrate. The droplets consist of a water-ethanol (7:3vol) mixture, with a density of 963 kg/m^3, a viscosity of 2.31 mPa·s, and a surface tension of 37.2 mN/m at 20°C. The droplets are dispensed by a 20 μm-radius inkjet nozzle (MicroFab MJ-AL-01-040) controlled by a function generator (Agilent 33220A) via a high-voltage amplifier (A. A. Lab A-301HS).

The launching process is visualized by an Infinity K2 microscope with a 10x Nikon objective, and captured with a Phantom v710 camera at 10,000 frames per second. Care is taken to ensure that the adaxial plane is parallel to the optical axis to within $\pm 5^\circ$. The launching velocity is extracted from the predominantly vertical launching trajectory, obtained by video tracking of the projected centroid of the particle-drop complex. The velocity is obtained from the time-lapsed spore position, which is fitted by a second-order polynomial to account for the gravitational deceleration [30]. Since the model spores are much larger than real ones, air friction plays a negligible role (which can typically be accounted for by a second-order polynomial fit too [30]). The slight density difference between the particle and the working fluid is neglected. The error bars in launching velocity are estimated from the uncertainties in microscopic video imaging.

S.3 Numerical Methods

The interfacial flow dynamics is simulated with the phase-field method, in which a variable Φ is introduced to describe the thin but diffuse interface, across which Φ continuously changes from 1 for the bulk liquid to -1 for the bulk gas. The flow is governed by the Navier-Stokes equations and the Cahn-Hilliard equation,

$$\boldsymbol{\nabla} \cdot \boldsymbol{V} = 0, \tag{S.1}$$

$$\rho \frac{\partial \boldsymbol{V}}{\partial t} + \rho \boldsymbol{V} \cdot \boldsymbol{\nabla} \boldsymbol{V} = -\boldsymbol{\nabla} P + \mu \nabla^2 \boldsymbol{V} + G \boldsymbol{\nabla} \Phi, \tag{S.2}$$

$$\frac{\partial \Phi}{\partial t} + \boldsymbol{V} \cdot \boldsymbol{\nabla} \Phi = \gamma \nabla^2 G, \tag{S.3}$$

where $\boldsymbol{V}$ is the velocity vector, ρ is the density, t is the time, P is the pressure, μ is the viscosity, γ is the mobility parameter, and G is the chemical potential. The Cahn-Hilliard chemical potential is given by $G = -\lambda \nabla^2 \Phi + \lambda \Phi (\Phi^2 - 1)/\epsilon^2$, where ϵ is the capillary width characterizing the thickness of the interface, and λ is the interfacial energy density. The fluid properties in the diffuse interface are averaged according to the local phase-field parameter, e.g. $\rho = \rho_L(1+\Phi)/2 + \rho_G(1-\Phi)/2$, where ρ_L and ρ_G are the density of the bulk liquid and gas, respectively; and $\mu = \mu_L(1+\Phi)/2 + \mu_G(1-\Phi)/2$, where μ_L and μ_G are the viscosity of the bulk liquid and gas, respectively. The boundary conditions on the solid surface are

$$\boldsymbol{V} = 0, \quad \boldsymbol{n} \cdot \boldsymbol{\nabla} G = 0, \quad \boldsymbol{n} \cdot \boldsymbol{\nabla} \Phi = \frac{\sqrt{2}}{2} \frac{\Phi^2 - 1}{\epsilon} \cos\theta, \tag{S.4}$$

where $\boldsymbol{n}$ is the normal vector of the solid surface. In equation (S.4), Young's contact angle θ is a reflection of the wall energy whose relaxation is assumed instant [29].

In the 3D simulations, the Ohnesorge number is kept at $Oh = 0.0126$ (except figure 6), which corresponds to a Buller's drop radius $r_B = 100\,\mu$m with the following water properties at 20°C: density ρ_L = 998 kg/m^3, viscosity μ_L = 1.071 mPa·s, and surface tension σ = 72.7 mN/m [20]. The air properties are inconsequential given the much smaller density and viscosity of the air. The contact angle is $\theta = 30^\circ$, although it is inconsequential with a pinned contact line. There are three model parameters, λ, ϵ, and γ. The interfacial energy density λ is related to the surface tension σ by $\sigma = (2\sqrt{2}/3)\lambda/\epsilon$. The capillary width ϵ needs to be sufficiently small to attain the sharp interface limit, and $\epsilon^* = \epsilon/r_B = 0.05$ is adopted in the 3D simulations [20]. The mobility parameter γ gives rise to a diffusion length $l_d = \sqrt{\gamma\mu}$, which is approximately proportional to the hydrodynamic slip length [29]. A small mobility parameter $\gamma^* = \gamma\sqrt{\rho\sigma/r_B^3} = 10^{-9}$ is adopted to effectively pin the triple line [21]. With a pinned contact line, the merged drop is not permitted to move below the near edge of the adaxial drop where the Buller-adaxial drop coalescence initiates. Although the near-edge pinning is essential, the contact line mobility at the far edge is not important. In figure 7, very similar flow fields at the point of launching are obtained with increasing adaxial radius, which effectively mobilizes the contact line at the far end.

The 2D simulations are used to vary the relative position between the Buller's drop and the adaxial drop, indicated by β in figure 9a inset. Except for the wedge setup depicted in figure 9a and a reduced dimensionality giving rise to $m_B = \pi\rho_L r_B^2$, the 2D numerical procedures are the same as their 3D counterparts. On the sharp wedge in figure 9 inset, the left edge has a contact angle $\theta = 30^\circ$ for the adaxial plane, while the slanted right edge is non-wetting with a contact angle of 180°. This setup permits the placement of the Buller's drop partly to the right of the adaxial plane, while enforcing the drop coalescence to proceed only on the adaxial plane. The Buller's drop is tangent to the adaxial drop whenever possible. At large β angles, e.g. $\beta > 71^\circ$ when $r_A/r_B = 2$ and $\psi_A = 30^\circ$, the Buller's drop is in contact with the adaxial drop at the tip of the wedge to ensure coalescence. Note that the positioning angle β depends on the relative size of the Buller's and adaxial drops, and the β values reported in figure 9 correspond to $r_A/r_B = 2$ and $\psi_A = 30^\circ$.

S.4 Supporting Movies

Movie S1 Model spore launching (figure 3): field of view = 1.2 mm×1.2 mm (duration $T = 7.5$ ms).
Movie S2 3D simulation (figures 4, 7a): $Oh = 0.0126$, $r_A/r_B = 2$ and $\psi_A = 30°$ (duration $T^* = 4.5$).
Movie S3 3D simulation (figure 7a): $Oh = 0.0126$, $r_A/r_B = 3$ and $\psi_A = 30°$ ($T^* = 4.5$).
Movie S4 3D simulation (figure 7a): $Oh = 0.0126$, $r_A/r_B = 4.5$ and $\psi_A = 30°$ ($T^* = 4.5$).
Movie S5 3D simulation (figure 7b): $Oh = 0.0126$, $r_A/r_B = 2$ and $\psi_A = 15°$ ($T^* = 4.5$).
Movie S6 3D simulation (figure 7b): $Oh = 0.0126$, $r_A/r_B = 3$ and $\psi_A = 15°$ ($T^* = 4.5$).
Movie S7 3D simulation (figure 7b): $Oh = 0.0126$, $r_A/r_B = 4.5$ and $\psi_A = 15°$ ($T^* = 4.5$).
Movie S8 2D simulation (figure 9): $Oh = 0.0126$, $r_A/r_B = 2$ and $\psi_A = 30°$ ($T^* = 4.5$).
Movie S9 Model spore launching (figure 10a): field of view = 1.2 mm×1.2 mm ($T = 7.5$ ms).