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TITLE: A SELF-SIMILAR APPROACH TO THE EXPLOSION OF DROPLETS BY A HIGH ENERGY LASER BEAM

AUTHOR(S): SHIRISH M. CHITANVIS

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A self-similar approach to the explosion of droplets by a high energy laser beam.

Shirish M. Chitanvis
Los Alamos National Laboratory, Theoretical Division, P-371
Los Alamos, New Mexico 87544.

ABSTRACT.

We have constructed a model in which a small droplet is exploded by the absorption of energy from a high energy laser beam. The beam flux is so high that we assume the formation of a plasma. We have a single-fluid model of a plasma droplet interacting with laser radiation. Selfsimilarity is invoked to reduce the spherically symmetric problem involving hydrodynamics and Maxwell's equations to quadrature. We show analytically that our mode! reproduces in a qualitative manner certain features observed experimentally by Eickmans et al.

I. Introduction.

Eickmans et al[1] have reported the explosion of water droplets of radius 35μm, by a laser beams with a flux $I \sim 10^9$ W/cm^2, and a pulse width τ_p of 20 nanoseconds. In these experiments, the laser beam is incident on the droplet, which acts as a convergent lens and causes focusing toward the rear of the droplet. The wavelength of the incident (Nd:YAG) laser is 0.532μm. One would not expect much thermal absorption in water at that wavelength. But due to the high flux of the beam and the focusing effect, the droplet ionizes.[1] The plasma then absorbs quite strongly from the beam, and the drop explodes with the formation of a layer of vapor. In the vapor,[1] we clearly see a decrease in the density followed by an increase. We theorize that the hot spot created within the droplet expels a mass of vapor. Far from the droplet, the temperature drops and the vapor becomes denser and then appears as a plume.

We have distilled the fundamental idea that the blow-off followed by cooling causes the non-monotonic beahvior,[1] and constructed a spherically symmetric model of the explosion which does indeed predict a plume.

II. The single-fluid model.

In the explosions reported by Eickmans et al,[1] we basically have ionized *fluid* streaming out of the droplet. But there is no compelling reason to treat the two components of this plasma separately with great

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[1] J.H. Eickmans, W.F. Hsieh and R.K. Chang, submitted to *Opt. Lett.*

care. We therefore simply consider the plasma to be a hydrodynamic fluid with a certain local velocity (v), mass density (ρ), temperature (T), pressure (P), a specific heat (C_v) and an absorption coefficient (α). For simplicity we shall consider the plasma to be perfect gas. We shall take C_v and α to be phenomenological parameters to be fitted using experimental data.

As discussed in a previous paper on explosions[2] we shall use the following self similar variable to simplify the coupled equations of hydrodynamics and electromagnetism:[2]

$$\xi = r/c(t+t_0) \qquad (2.1)$$

where c is the surface speed given approximately by the conservation of energy:[3]

$$c \approx \sqrt{(2\,\alpha'\, I\, \tau_p / \rho_0)} \qquad (2.2)$$

where $\alpha' = 3\alpha/4a_0$, α being a dimensionless absorption efficiency, a_0 is the unperturbed droplet radius, I is the flux of the beam (W/cm^2), τ_p is the pulse length, and ρ_0 is the unperturbed density.

If we make the ansatz[2,3] that $\rho(r,t) = \rho'(\xi)$, $v(r,t) = v'(\xi)$, $T(r,t) = T'(\xi)$, $E(r,t) = F'(\xi)$, and we assume a perfect gas law for ease of computations:

$$P(\xi)\rho^{-1}(\xi) = R_g T(\xi) \qquad (2.3)$$

we get the following set of coupled ordinary differential equations, using $F(\xi) = 1/\xi$ (please see references 2 and 3 for details):

$$dv(\xi)/d\xi = 2\kappa_2[(v(\xi)-\xi)^2 - \kappa_2(\kappa_3-1)T(\xi)]^{-1}$$

$$[\,(\kappa_3+1)v(\xi)T(\xi)/\xi + \kappa_1\,\xi\,(d/d\xi\,|F(\xi)|^2)/(2\rho(\xi))\,] \qquad (2.4)$$

$$dT(\xi)/d\xi = -\kappa_3 T(\xi)(dv(\xi)/d\xi+2v(\xi)/\xi)/(v(\xi)-\xi)$$

$$-\kappa_1\,\xi(d/d\xi\,|F(\xi)|^2)/(\rho(\xi)\,(v(\xi)-\xi)) \qquad (2.5)$$

$$d\rho(\xi)/d\xi = -\rho(\xi)(dv(\xi)/d\xi+2v(\xi)/\xi)/(v(\xi)-\xi) \qquad (2.6)$$

$$d^2F(\xi)/d^2\xi^2 = -2F(\xi)/\xi \qquad (2.7)$$

where ρ, v, T, F are normalized functions as follows: $\rho(\xi) = \rho'(\xi)/\rho_{(0)}$, $v(\xi) = v'(\xi)/c$, $T(\xi) = T'(\xi)/T_{(0)}$, $F(\xi) = F'(\xi)/F'(\xi=1)$, where $\rho_{(0)}$ is the density of the droplet at the surface, $T_{(0)}$ is the temperature of the drop at

[2] S.M. Chitanvis, *Physica 137A*, 271, (1986)

[3] S.M. Chitanvis, *CRDEC Conference Proceedings* (1986)

the surface, and c is the speed of the surface. We also need the following definitions: $\kappa_1 = \alpha \,|F'(\xi=1)|^2/(8\pi C v T_{(0)}\rho_{(0)} c)$, $\kappa_2 = RgT_{(0)}/c^2$, $\kappa_3 = Rg/Cv$.

III. The analysis.

Notice that in Eqn (2.4)-(2.6), there is a potential source of singularity when $\rho(\xi) \to 0$ or $v(\xi) \to \xi$ for some $\xi = \xi^*$.

We shall perform a local analysis of the solution for $\xi_1=\xi^*+\delta\xi \le \xi \le \xi_2=\xi^*+\delta\xi$. $\delta\xi \to 0^+$ when $v(\xi) = v^* \approx \xi^*$. We shall take $dv/d\xi = 0$ here. This assumption was suggested by our earlier[2] numerical solution of the problem. This leads to the identity:

$$T(\xi) = \kappa_1/(v^*(\kappa_3+1))\ (1/\rho(\xi))\ (1/\xi) \quad (3.1)$$

From Eqn. (2.13) we get:

$$\rho(\xi) \approx \rho(\xi_1)\,[\ (v^*-\xi)/(v^*-\xi_1)/\xi\ ]^2 \quad (3.2)$$

This yields:

$$T(\xi) \approx \kappa_1/(\rho(\xi_1)(\kappa_3+1))\ [(v^*-\xi_1)/(v^*-\xi)]^2 \quad (3.3)$$

It is easy to show that Eqn (3.3) satisfies Eqn (2.5) approximately for $\xi \approx \xi^*$.

Thus we see that at the singular point $\xi = \xi^*$, the density dips to zero, then starts to rise. The temperature on the other hand, has a second order pole at $\xi = \xi^*$. This is not unphysical behaviour, since the total energy of the fluid viz. $1/2\rho v^2 + \rho C_v T$ remains finite.

Far beyond this dip, for some $\xi \ge \xi_a$ we can get the asymptotic behaviour of the hydrodynamic variables. We again take $dv/d\xi = 0$, and $v(\xi \to \infty) = v_0$ so that:

$$\rho(\xi) \approx \rho(\xi_a)\ \exp[-2v_0\ (1/\xi - 1/\xi_a)\ ] \quad (3.4)$$

$$T(\xi) \approx [\ \kappa_1 v_0/\rho(\xi_a)(\kappa_3+1)]\ (1/\xi)\ \exp[2v_0\ (1/\xi - 1/\xi_a)\ ] \quad (3.5)$$

Eqn. (3.5) satisfies Eqn. (2.5) approximately, as long as κ_1 (which is dimensionless) $\ll 1$. For $I \le 10^{12}$ W/cm^2, this condition is satisfied.

We therefore have the following picture of the density; it starts off at some value $\rho(\xi=1)$ at the surface, decreases to zero, and then tends to an asymptotic value if there is no ambient medium around the spherically exploding droplet. In the presence of an ambient medium, the motion stops at $\xi = 1 + ct'/(\text{initial radius})$, where t' is the time past the explosion.

We therefore see analytically in our model that a spherical *plume* or *blowoff* is formed around the exploding droplet. This is analogous to the plume seen in experiments.[1]