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STRUCTURE AND SCALING LAWS OF LASER-DRIVEN ABLATIVE IMPLOSIONS

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ABSTRACT

A stationary, spherical flow model gives the form of laser-driven ablation fronts and scaling laws for the dependence of implosion parameters on laser wavelength, pusher atomic number, and other input quantities.

One of the major deficiencies of the theory of laser-driven implosions has been the lack of even approximate analytic relationships between the specified parameters, material description, radius, absorbed laser power and wavelength, and the resulting ablation pressure and mass flow rate. Consequently, numerical simulation parameter studies of laser fusion events[1] are guided primarily by intuition and may overlook important optima, in addition to being difficult to understand, because the number of variable parameters is so large. Planar geometry stationary flow models of the ablation process have given some qualitative insight[2] but have failed to provide useful formulae because the exhaust velocity is sonic. In contrast with supersonic blow-off from spherical ablation, the exhaust density is the critical density and the resulting scalings are independent of the thermal conduction law of the material and have little or no relevance to spherical implosions. The crucial missing feature of these models is the nozzling effect of spherical expansion. The model proposed here overcomes these deficiencies and produces useful scaling laws.

In this model the flow is spherically symmetric, radially outward, and stationary. Stationary flow is a reasonable approximation in most cases of interest because the time required to establish the flow between the pellet surface and the critical surface (where absorbed energy is assumed to be deposited) is less than the characteristic implosion time and because the pressure gradient forces in the ablation region are larger than the forces associated with the average inward acceleration. The heat and fluid flow are described by the equations:

$$\frac{d\tilde{v}}{d\tilde{r}} = \frac{\tilde{T}}{\tilde{v}} \frac{\left(\frac{2}{\tilde{r}} - \frac{1}{\tilde{T}}\frac{d\tilde{T}}{d\tilde{r}}\right)}{\left(1 - \frac{\tilde{T}}{\tilde{v}^2}\right)} \tag{1}$$

$$\frac{d\tilde{T}}{d\tilde{r}} = \frac{M\left[\frac{1}{2}\left(\tilde{v}^2 - \tilde{v}_B^2\right) + \eta\,\tilde{T}\right]}{\tilde{r}^2\,\tilde{T}^{5/2}} \tag{2}$$

where

$$M \equiv (Zr_s\, v_s^2\, S/T_s)/(4\pi\, r_s^2\, \kappa_o\, T_s^{5/2}), \quad \text{(dimensionless const)}, \tag{3}$$

and where the electron thermal conductivity, constant mass flow rate, and pressure are

$$\kappa = \kappa_o\, T^{5/2}/Z\ (\kappa_o = \text{const})^3,\ S = 4\pi\, r^2\, \rho v, \text{ and}\quad P = \rho RT/\mu. \tag{4}$$

r_s, v_s, T_s, etc., are the radius and values of various quantities at the <u>isothermal</u> sonic point and $\tilde{r} \equiv r/r_s$, $\tilde{v} \equiv v/v_s$, etc. $\tilde{v}_B^2/2$ is the Bernoulli energy constant, $\eta = \gamma/(\gamma-1)$, and all other definitions are standard. The numerical solution of these equations is best done by integrating inward $(\tilde{r} < 1)$ and outward $(\tilde{r} > 1)$ from the singularity of Eq. 1 at $\tilde{r} = 1$. Requiring physical solutions with $d\tilde{v}/d\tilde{r} >$

0 at $\tilde{r} = 1$ and $\tilde{v}_B^2 > 0$ restricts M to the range $2/3 < M < 3.2$ (when $\gamma = 5/3$). It is seen from Eq. 1 that solutions passing smoothly through $\tilde{r} = 1$ must have $d\tilde{T}/d\tilde{r} > 0$. The critical point (density) must, therefore, occur outside of the isothermal sonic point but may occur inside of the adiabatic sonic point. Figure 1a and b shows a set of solutions for $M = 0.67$ and 0.90 and various values of $\rho_{c(ritical)}/\rho_s$. The input power at r_c is adjusted to give the solution T(r) that approaches 0 asymptotically as $r \to \infty$. The model assumes that the pellet outside radius, r_p, is the point where $dv/dr = 0$. Inside of this point the flow is essentially adiabatic subsonic expansion. The ablation front may be thought of as the region $r_p < r < r_s$. Figure 2a, ratios of scaled quantities at r_p as a function of M, shows that ρ_p and T_p may vary widely while P_p/P_s remains about the same, ~ 2, for all solutions in the usually interesting range $2/3 < M \leq 1$. Also note that P_p is essentially independent of ρ_p (see also Eq. 7 below). Figure 2b, various dimensionless quantities including the total absorbed laser power, $F \equiv W/(S\, v_s^2/2)$, as a function of ρ_c/ρ_s and therefore wavelength, λ, for a few values of M, shows that the M dependence of structure outside of r_s is very weak and that the power required to support a given ablation structure and P_p, in particular, scales approximately as

$$W \sim \rho_c^{-1/2} \sim \lambda. \qquad (5)$$

However, as λ increases and ρ_c/ρ_s becomes sufficiently small, the stationary flow approximations weaken and the W required in a real event will not increase as rapidly as Eq. 5.

Using Eqs. 4 and 5 and an estimate of the maximum possible pressure P_{max}, one can derive a relative thermal coupling effectiveness ε relating laser power to ablation pressure P_p. Suppose that the laser power reaches the pellet surface ($r_p = r_s = r_c$) and is there entirely converted to outward mass motion. Then $W/A_p = \rho_p v_p^3/2$ and since $P_{max} = \rho_p v_p^2$, we obtain $P_{max} = \sqrt{2\, S\, W/A_p}$ where $A = 4\pi r^2$. Then

$$\varepsilon \equiv P_p/P_{max} = (P_p/P_s)\,(r_p/r_s)^2/\sqrt{F} \qquad (6)$$

and from Eq. 5 $\varepsilon \sim \lambda^{-1/2}$ for given pellet conditions. Evaluating Eq. 6 using Figs. 2a and b, we obtain $\varepsilon_{max} = 52\%$ for $M = 2/3$ and $\rho_c/\rho_s = 1.0$ while $\varepsilon \approx 22\%$ for $M = 0.9$ and $\rho_c/\rho_s = 0.1$ for example.

Further scaling laws can be obtained from Eqs. 3 and 4, and Fig. 2a. From Eqs. 3 and 4 using $\mathcal{R} = R/\mu$ we obtain

$$P_s = M\,\kappa_o\,T_s^3/(Z\,r_s\,\mathcal{R}^{1/2}) \qquad (7)$$

$$\rho_s = M\,\kappa_o\,T_s^2/(Z\,r_s\,\mathcal{R}^{3/2}) = \left[\frac{M\,\kappa_o}{Z\,r_s\,\mathcal{R}^{1/2}}\right]^{1/3} P_s^{2/3}/\mathcal{R} \qquad (8)$$

$$S = 4\pi r_s\,M\,\kappa_o\,T_s^{5/2}/(Z\,\mathcal{R}) = \frac{4\pi r_s}{Z\mathcal{R}}\,M\,\kappa_o\left[\frac{Z\,P_s\,r_s\,\mathcal{R}^{1/2}}{M\,\kappa_o}\right]^{5/6}. \qquad (9)$$

From the near constancy of P_p/P_s and r_p/r_s (Fig. 2a) and the fact that the range of M is quite small, these equations with P_s and r_s replaced by P_p and r_p multiplied by 2.0 and 0.8, respectively, are approximately applicable to the pellet surface. From Eq. 7 then, a T^3 dependence for ablation pressure is obtained, as well as a Z^{-1} dependence. The latter can be used to obtain the same kind of improved compression as is obtained from a shaped pulse[1] by designing pellet ablation layers with Z increasing as r increases and using a simpler pulse. From pellet surface parameters, Eq. 8 and recursive use of Fig. 2a, values of M can be obtained if desired.

Finally, from Eq. 9 for the mass ablation rate one can obtain a scaling law for the dependence on Z of the maximum average ablation pressure and specific kinetic energy obtainable in those thin shell pellets which are now believed to be most desirable for laser fusion.[4] An implosion time τ can be estimated in terms of the initial radius r_i, the shell mass m, and an average, in some sense, of the force P_p A,

$$\tau \simeq (2 r_i m/\langle P_p\,A\rangle)^{1/2}. \qquad (10)$$

If the fraction of the shell mass to be ablated away for maximum energy transfer is f ($f \simeq 0.8$. see Brueckner and Jorna, Ref. 2, P. 346), then the average ablation rate should be $\langle S\rangle \simeq fm/\tau = f(\langle P_p\,A\rangle\, m/2r_i)^{1/2}$. This together with Eq. 9 implies that $\langle P_p\rangle \sim Z^{1/2}$. Since the specific kinetic energy E in an implosion with a given r_i and average velocity is proportional to τ^{-2} we have

$$E \sim \langle P_p \rangle \sim Z^{1/2}. \qquad (11)$$

This further implies that if E is kept fixed while the shell size is increased with $m \propto r_i^3$ ($\rho\Delta r/r_i$ fixed), then $r_i Z$ should be kept fixed. That is, Z should decrease with increasing r_i.

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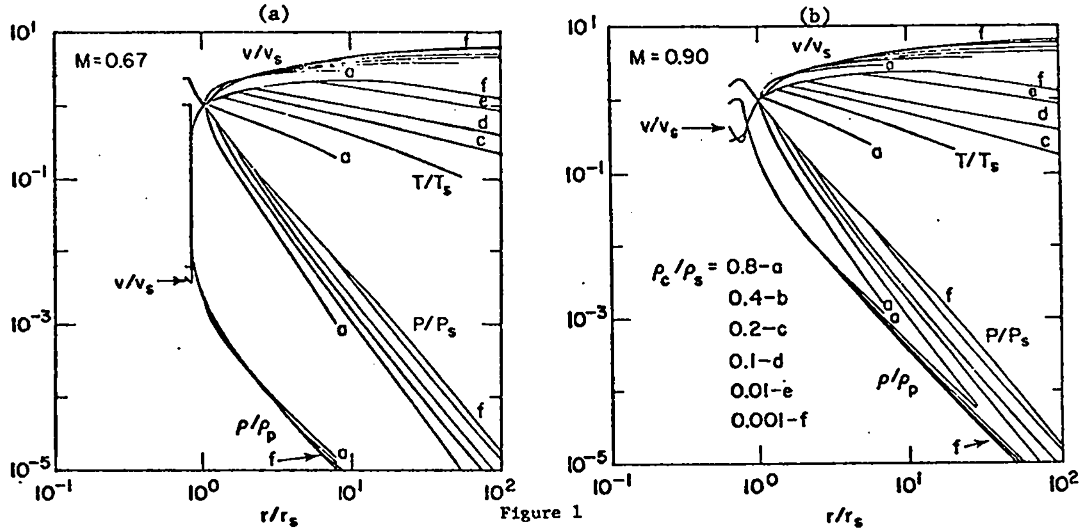

Figure 1

Solutions of Eqs. 1 and 2 for (a) $M = 0.67$ and (b) $M = 0.90$ for a range of ρ_c/ρ_s values.

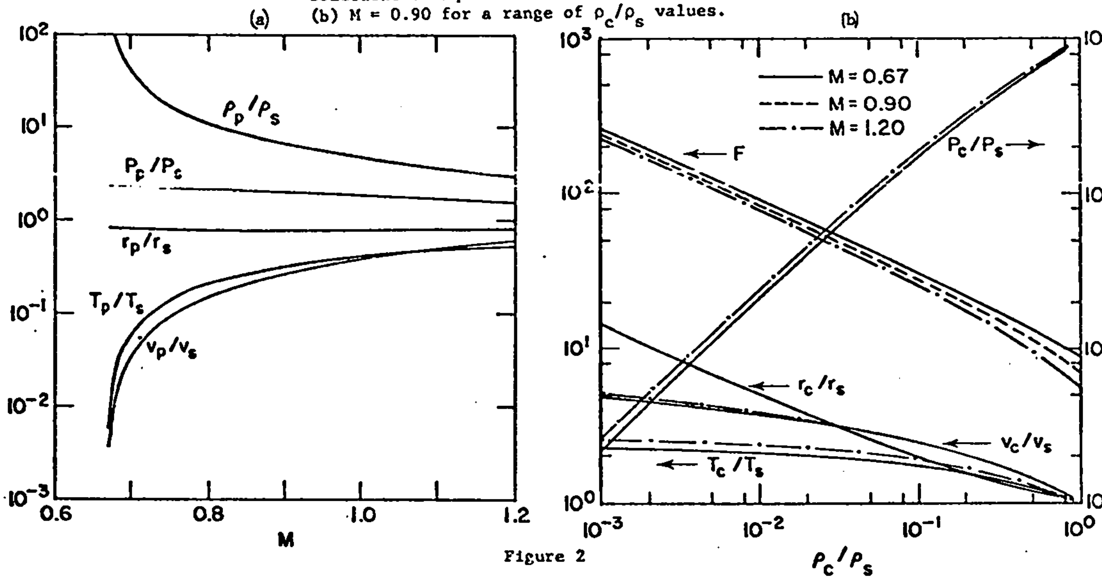

Figure 2

(a) Scaled flow variables evaluated at the pellet surface $r = r_p$ (where $dv/dr = 0$) as functions of M. (b) Scaled flow variables and dimensionless laser power F as functions of ρ_c/ρ_s with additional weak M dependence shown.