SELF-SIMILAR DEFLAGRATION IN LASER HALF-SPACE PLASMAS

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Abstract: The self-similar motion of a half-space plasma, generated by a linear pulse of laser radiation absorbed anomalously at the critical density, has been studied. The resulting plasma structure has been completely determined for [pulse duration × (critical density)^2/maximum irradiation] large enough.

In laser fusion schemes, laser radiation is absorbed in a plasma at electron densities less than, or around, the critical density n_c. If $\epsilon \equiv n_c/n_o \ll 1$, n_o being the initial density, absorption occurs in a hot and rarefied corona, ablated by the laser [1]. Entropy (which is generated there) should be kept low inside the dense plasma, where mass and energy should converge efficiently; in addition the energy coronal outflow should be minimized. Thus, hydrodynamics plays an essential part in microfusion.

We have studied the self-similar motion of a plasma under irradiation of a laser pulse linear in time [2], [3]. The plasma at $t=0$ is assumed to occupy the half-space $x>0$, with uniform density n_o and negligible temperature; the pulse irradiation

$$\phi = \phi_o\, t/\tau \;, \qquad 0<t\leq\tau \qquad (1)$$

is assumed absorbed at the plane where the electron density n_e equals n_c. The analysis allows for electron thermal conductivity and different temperatures, T_e and T_i (an electron flux limiter, viscosities, and ion heat conduction could be also included in the self-similar solution); we consider neither nuclear fusion, nor radiation pressure and emission.

We make the ansatz (verified in the solution) that the plasma is both quasineutral and collision-dominated. From $n_e = n_i \equiv n$ we then get equal ion and electron velocities, $v_e = v_i \equiv v$. For the electron thermal conductivity and the ion-electron relaxation time we may use the classical results [4]

$$K_e \equiv \bar{K}_e T_e^{5/2} \;, \qquad t_{ei} = \bar{\tau}_{ei} T_e^{3/2}/n$$

where the Coulomb logarithms in $\bar{K}_e$ and $\bar{\tau}_{ei}$ are assumed to remain constant.

Defining appropriate dimensionless variables

$$\xi = x/w\tau(t/\tau)^{4/3} \;, \qquad u(\xi) = 3v/4w(t/\tau)^{1/3}$$
$$\bar{n}(\xi) = n/n_o, \quad \theta_j = T_j/T_o(t/\tau)^{2/3}, \quad \alpha = 9kT_o/4m_i w^2 \qquad (2)$$

the equations of continuity for either species, momentum for the ion-electron fluid, and entropy for each species, read

$$(\xi-u)\,d\bar{n}/d\xi = \bar{n}\, du/d\xi$$

$$u-4(\xi-u)\frac{du}{d\xi} = -\frac{\alpha}{\bar{n}}\frac{d}{d\xi}\left[\bar{n}(\theta_e+\theta_i)\right]$$

$$\bar{n}\left[\theta_i\left(1+\frac{4}{3}\frac{du}{d\xi}\right)-2(\xi-u)\frac{d\theta_i}{d\xi}\right] = 4.3\,\alpha\,\bar{n}^2\,\frac{\theta_e-\theta_i}{\theta_e^{3/2}} \qquad (3)$$

$$\bar{n}\left[\theta_e\left(1+\frac{4}{3}\frac{du}{d\xi}\right)-2(\xi-u)\frac{d\theta_e}{d\xi}\right] = \frac{d}{d\xi}\left(\theta_e^{5/2}\frac{d\theta_e}{d\xi}\right)-4.3\,\alpha\,\bar{n}^2\,\frac{\theta_e-\theta_i}{\theta_e^{3/2}}+\delta(\xi-\xi_c)$$

with boundary condition

$$\theta_e=\theta_i=u=\bar{n}-1=0 \qquad \text{at} \quad \xi=\infty$$
$$\bar{n}=u-\xi_v=0 \qquad \text{at} \quad \xi=\xi_v \qquad (4)$$

where ξ_v is the position of the plasma-vacuum boundary and ξ_c is given by

$$\bar{n}(\xi_c) = \bar{n}_c \equiv \epsilon \;.$$

In Eqs. (3) we have chosen w and T_o to satisfy

$$w = (\phi_o^5 \bar{K}_e^2/k^7 n_o^7 \tau^2)^{1/9}, \quad T_o = (\phi_o^2 \tau/\bar{K}_e k n_o)^{2/9}$$

and then

$$\alpha = (9k/4m_i)(k^2 n_o^2 \tau/\phi_o \bar{K}_e)^{2/3} \;;$$

k is Boltzmann's constant and m_i the ion mass.

Assuming $\alpha \gg \epsilon^{-4/3}$ [that is, $\alpha_c \equiv \alpha(n_c/n_o)^{4/3} \gg 1$] we find that the flow presents three main regions. An isentropic compression to the right, beginning at a shock bounding the undisturbed plasma at ξ_f, and ending at $\bar{\eta}\xi_f$, where

$$\xi_f = .53\,\epsilon^{1/6}\alpha^{1/3} \;, \qquad \bar{\eta} = .82 \;.$$

A much larger isentropic expansion to the left, lying between $\bar{\eta}\xi_f$ and $\xi_v = -2.19\,\epsilon^{-1/2}\xi_f$, so that in this region, $\bar{\eta}\xi_f$ is indistinguishable from zero. A deflagration layer (where absorption occurs, conduction is important, and $\theta_e \neq \theta_i$) separating the isentropic regions; its width is of the order of $\epsilon^{-5/2}\alpha^{-3/2}\xi_f$, so that deflagration and isentropic expansion merge into each other when $\alpha = O(\epsilon^{-4/3})$, while the relative size of the deflagration and the isentropic compression depends on the value of $\epsilon^{-5/2}\alpha^{-3/2}$. Detailed results are given in the figure.

REFERENCES

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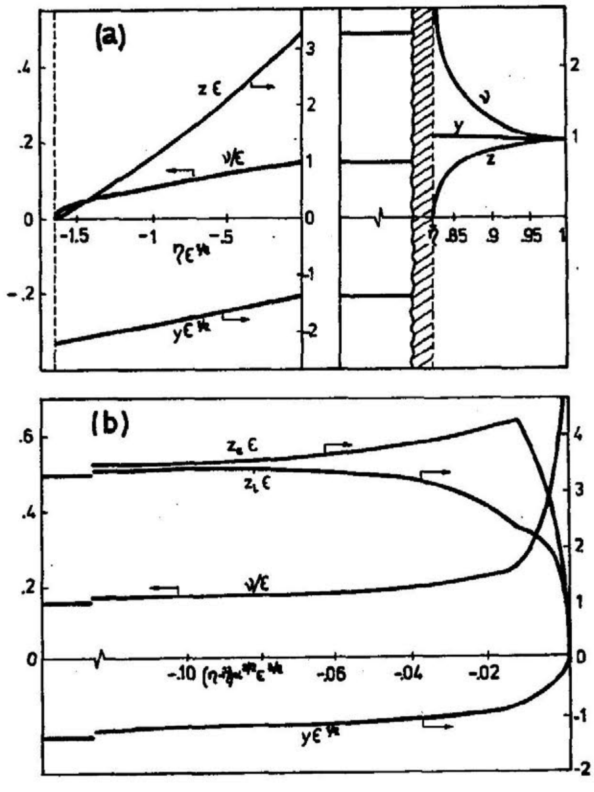

a) Isentropic expansion and compression regions. b) Deflagration layer; $\eta = \xi/\xi_f$, $y = 4u/3\xi_f$, $z_j = 8\alpha\theta_j/3\xi_f^2$, $\nu = \bar{n}/4$.