Boris Lukiyanchuk

Laser - matter interactions

Lecture 5.

Singapore, 13 November 2019

Laser - matter interactions

Nonresonant processes

- Physical Processes
- Chemical Processes
- Vapor Plasma Processes

Resonant processes

- Plasmonics Photonics
- Nonlinear Optics
- Resonant Chemistry

Lecture 5.

Vapor Plasma Processes

Intensive laser illumination of solid or liquid target leads to formation of vapor plume. This process plays important role in applications, e.g. pulsed laser deposition.

Pulsed Laser Deposition

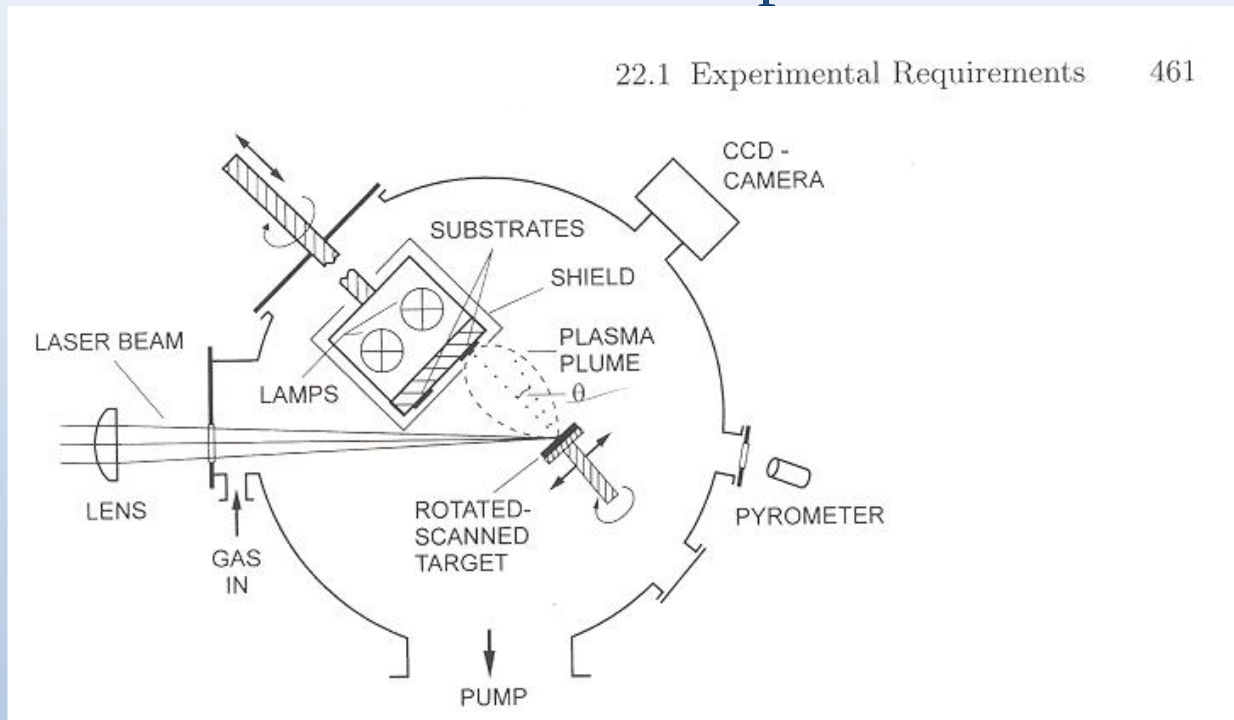
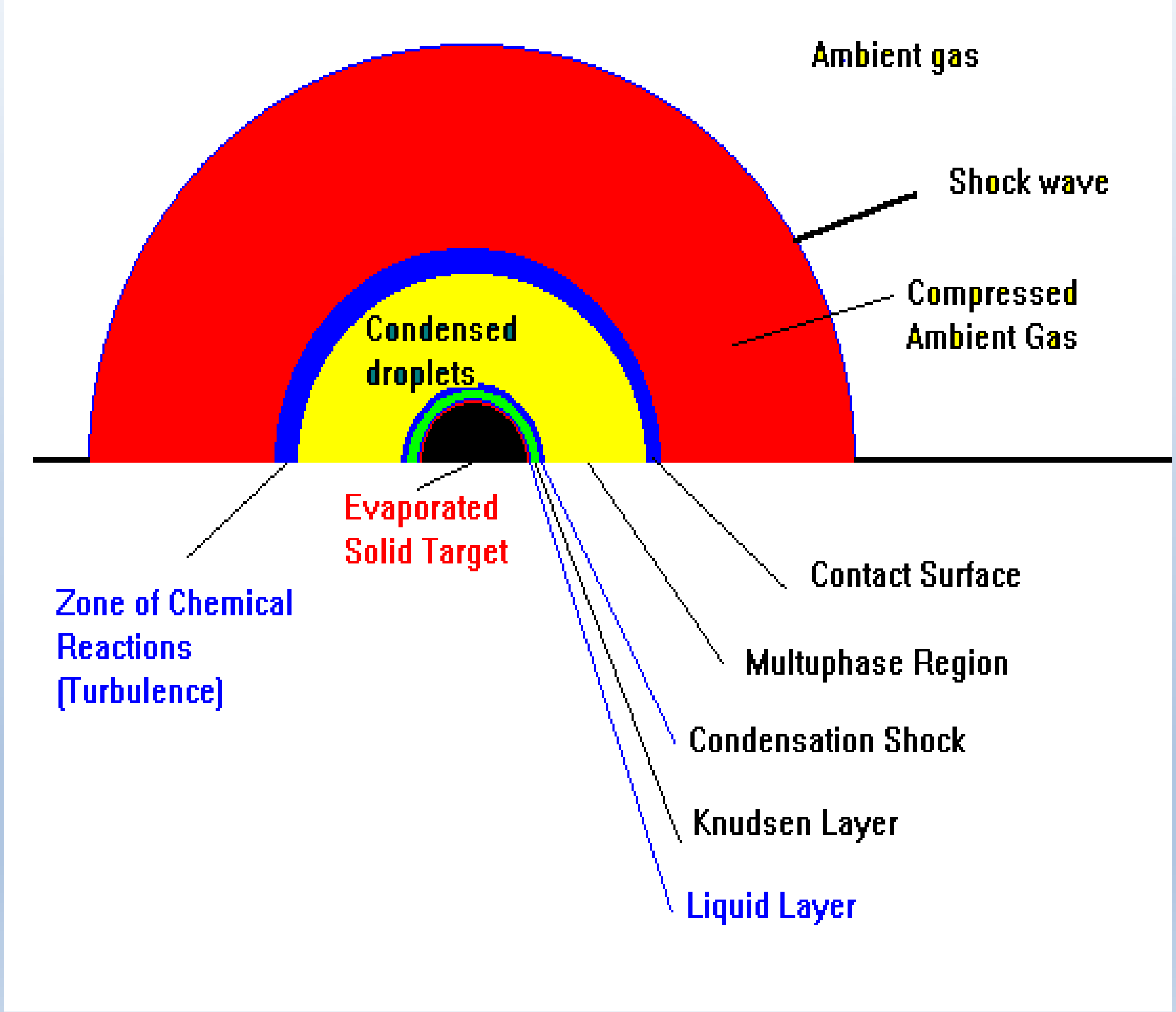


Fig. 22.1.1. Schematic of an experimental setup employed in PLD. A CCD-camera is frequently employed in plasma-plume analysis

- The synthesis of metastable materials
- The formation of thin films
- The fabrication of nanocrystalline films
- The fabrication of composite films consisting of different materials

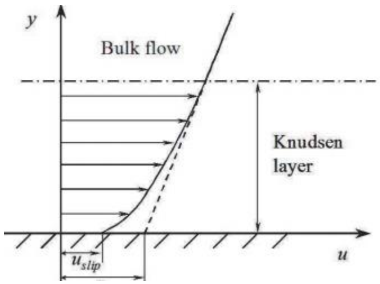
Pulsed laser deposition is accompanied by a number of physical processes

Laser Produced Vapor Plume



Martin Knudsen
1871 – 1949

At the interface of a vapor and a liquid/solid, the gas interaction with the liquid/solid dominates the gas behavior, and the gas is, very locally, not in equilibrium. This region, several mean free path lengths thick, is called the **Knudsen layer**. The thickness of this layer can be approximated by



$l_{Kn} = \dfrac{k_B T_s}{\pi d^2 p_s}$, where k_B is Boltzmann's constant, T_s is the temperature, d is the molecular diameter and p_s is the pressure.

M. Knudsen, *Thermischer Molekulardruck der Gase in Röhren*, Ann. Phys. **33**, 1435 (1910).

Sergei Anisimov
1934 -

Vaporization of metal absorbing laser radiation

S. I. Anisimov, JETP **27**, 182 (1968)

Atoms, emitted from the surface have a "half-Maxwell" velocity distribution for particles moving from an evaporating surface $v_z > 0$

$$f_1(\mathbf{v}) = n_1 \left(\frac{m}{2\pi k_B T_1} \right)^{3/2} exp\left[- \frac{m\left(v_x^2 + v_y^2 + v_z^2\right)}{2\, k_B\, T_1} \right], \qquad v_z > 0,$$

where T_1 is the wall temperature and one n_1 is the equilibrium density of saturated vapor at this temperature, $n_1 = n_s\,(T_1)$. "Far away" from the surface, atoms have a locally equilibrium distribution function

$$f_\infty(\mathbf{v}) = n_\infty \left(\frac{m}{2\pi k_B T_\infty} \right)^{3/2} exp\left[-m \frac{v_x^2 + v_y^2 + (v_z - u_\infty)^2}{2 k_B T_\infty} \right],$$

where is the temperature T_∞ and density n_∞ differ from their values T_1 and n_1 near the wall. Moreover, distribution $f_\infty(v)$ has an average drift velocity u_∞. The typical distance over which the distribution $f_\infty(v)$ is established is of the order of the particle's mean free path (thus, "infinity" actually means distance about the thickness of the Knudsen layer). Therefore, in the hydrodynamic approximation, the Knudsen layer can be considered as a discontinuity. In order to determine the structure of the transition layer, it is necessary to solve the Boltzmann kinetic equation. In the strongly nonequilibrium case we assume that the distribution of particles with velocities directed to the surface ($v_z < 0$) is proportional to the distribution at "infinity": $f_1(v_z) = \beta f_\infty(v_z)$, where β is some constant that describes the reverse flow. Thus, we must define four unknown constants u_∞, n_∞, T_∞ and β.

The problem, however, is that we do not know the mass velocity u_∞, the gas on the outer surface of the Knudsen layer. To determine this velocity, one must additionally solve the equations of gas dynamics for the vapor expansion. Suppose that the velocity u_∞ is known. Then the result of solving the corresponding problem can be presented in terms of the Mach number $Ma = \frac{u_\infty}{c_s(T)}$, where c_s is the local speed of sound in gas. In the case of laser evaporation with small and moderate laser intensity, the vapor flow is subsonic, $Ma < 1$. For an ideal gas with an adiabatic index $\gamma = c_p/c_v$, the local speed of sound is

$$c_s(T) = \sqrt{\gamma \frac{k_B T}{m}} \qquad \text{Thus,} \qquad u_\infty = Ma\sqrt{\gamma \frac{k_B T_\infty}{m}}$$

Three unknown constants can be found from the laws of conservation of mass, momentum, and energy flow, see e.g. H. M. Mott-Smith, *The solution of the Boltzmann equation for a shock wave*. Phys. Rev. **82**, 885, (1951).

$$\frac{n_1}{n_\infty}\sqrt{\frac{T_1}{T_\infty}} = 2\sqrt{\pi}\,\mu\left[1+\beta\,\Psi_1\right],$$

$$\frac{n_1}{n_\infty}\frac{T_1}{T_\infty} = 4\mu^2\left[1+\frac{1}{2\mu^2}+\beta\,\Psi_2\right],$$

$$\frac{n_1}{n_\infty}\left(\frac{T_1}{T_\infty}\right)^{3/2} = \frac{2(\gamma-1)}{\gamma+1}\left[\mu\sqrt{\pi}\left(2\mu^2+5+\frac{5-3\gamma}{\gamma-1}\right)+\beta\left(\mu\sqrt{\pi}\,\frac{5-3\gamma}{\gamma-1}\Psi_1-\Psi_3\right)\right],$$

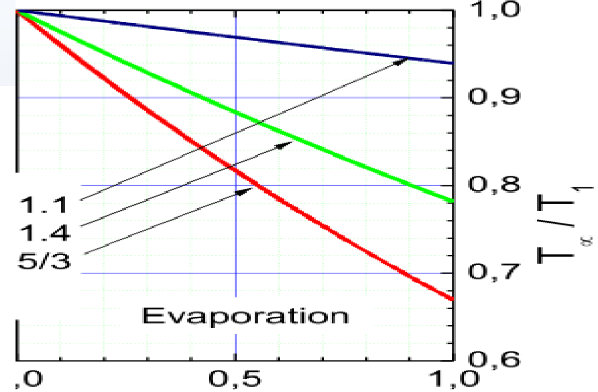
where

$$\Psi_1=\frac{1}{2}\left[\frac{e^{-\mu^2}}{\mu\sqrt{\pi}}-erfc(\mu)\right], \qquad \Psi_2=\frac{1}{2}\left[\frac{e^{-\mu^2}}{\mu\sqrt{\pi}}-\left(1+\frac{1}{2\mu^2}\right)erfc(\mu)\right],$$

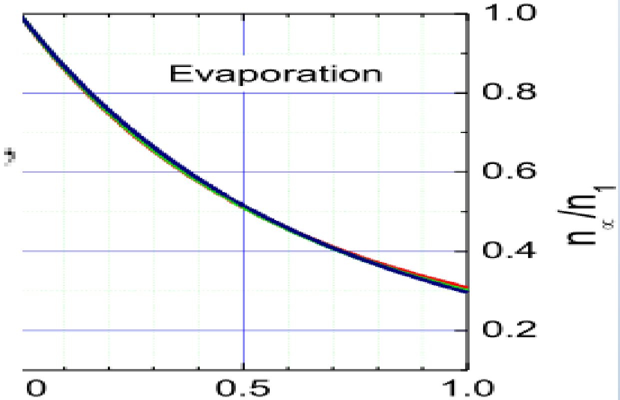
$$\Psi_3=\mu\left(\mu^2+\frac{5}{2}\right)\sqrt{\pi}\;erfc(\mu)-\left(\mu^2+2\right)e^{-\mu^2}, \qquad \mu=Ma\sqrt{\frac{\gamma}{2}}\;.$$

Finally, solution is

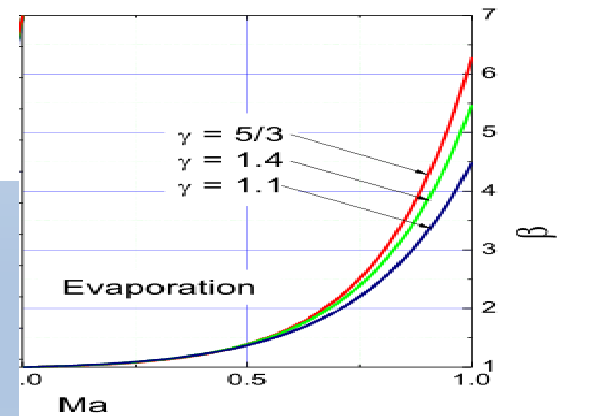
$$\frac{T_\infty}{T_1} = F_T(\gamma, Ma) \equiv \left\{ \sqrt{1+\pi\left(\frac{\gamma-1}{\gamma+1}\frac{\mu}{2}\right)^2} - \sqrt{\pi}\,\frac{\gamma-1}{\gamma+1}\,\frac{\mu}{2} \right\}^2 ,$$



$$\frac{n_\infty}{n_1} = F_n(\gamma, Ma) \equiv \mu\, e^{\mu^2}\left[\sqrt{\pi}\,\Psi_1 \frac{T_1}{T_\infty} - 2\,\mu\,\Psi_2 \sqrt{\frac{T_1}{T_\infty}}\right] ,$$



$$\beta\,(\gamma, Ma) = \frac{1}{\Psi_1}\left[\frac{1}{2\sqrt{\pi}\,\mu}\,\frac{n_1}{n_\infty}\sqrt{\frac{T_1}{T_\infty}} - 1\right].$$



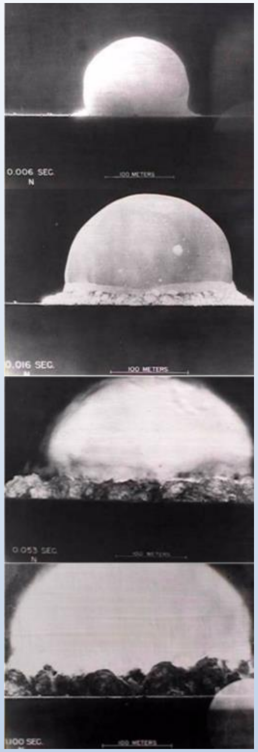
Another useful characteristic of the evaporation process is the ratio of the fluxes directed from the wall, J_+, to the wall (reverse flow), J_-: $\frac{J_-}{J_+} = \frac{\beta\Psi_1}{1+\beta\Psi_1}$

Of particular interest is also the pressure $P = n\,k_B T$ jump

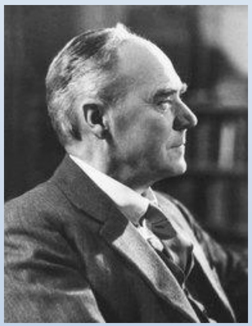
$\frac{P_\infty}{P_1} = \frac{n_\infty T_\infty}{n_1 T_1}$. For $Ma = 1$ and $\gamma = 5/3$

$$\frac{T_\infty}{T_1} = 0.669, \quad \frac{n_\infty}{n_1} = 0.308, \quad \frac{P_\infty}{P_1} = 0.206, \quad \beta = 6.286, \quad \frac{J_-}{J_+} = 0.184.$$

Self-similar solution of fluid dynamics and gas dynamics equations.



The first explosion of an atomic bomb was the Trinity test in New Mexico in 1945. Several years later a series of pictures of the explosion, along with a size scale, and time stamps were released and published in a popular magazine. Based on these photographs a British physicist named G. I. Taylor was able to estimate the power released by the explosion (which was still a secret at that time).



Sir Geoffrey Taylor
1886 – 1975

John von Neumann
1903 – 1957

Lev Sedov
1907 - 1999

L.L. Sedov, *Propagation of strong shock waves*, J. Appl. Math. Mech. **10**, pp. 241-250 (1946).
John von Neumann, Chapter 2, *Point source solution*, in Los Alamos scientific laboratory Report LA-2000, (1947).
G. Taylor, *The Formation of a Blast Wave by a Very Intense Explosion. I. Theoretical Discussion*. Proc. Royal Society A **201, pp.** 159–174 (1965).

We have the size of the fire ball (***R*** as a function of ***t***) at several different times. How does the radius ***R*** depend on: energy ***E*** , time ***t*** and the density of the surrounding medium (***ρ*** – initial density of air). $[R] = L$, $[E] = M\,L^2/\,T^2$, $[t] = T$, $[\rho] = M/\,L^3$

$$R = \beta\left(\frac{E\,t^2}{\rho}\right)^{\frac{1}{5}}$$

$\beta \approx 1$

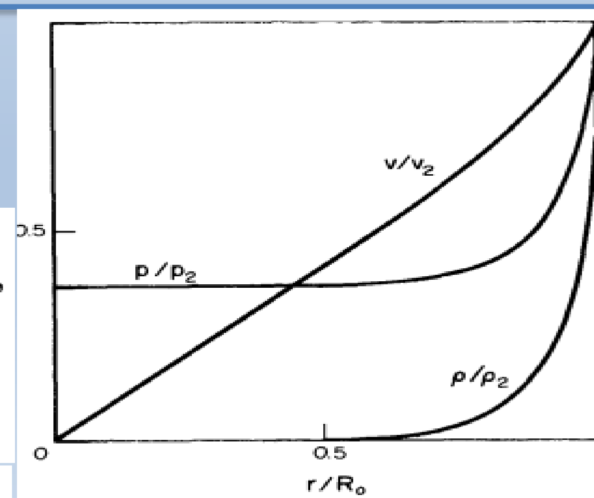
$$E = \frac{R^5\rho}{t^2} = 25\ \text{kilo} - \text{tons of TNT}$$

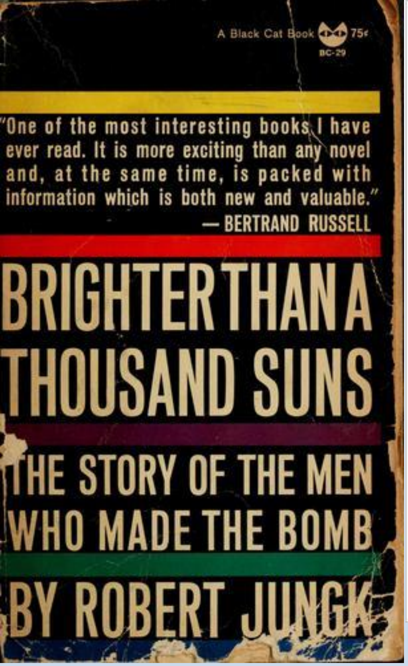
$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial r} = -\frac{1}{\rho}\frac{\partial p}{\partial r}, \qquad \frac{\partial \rho}{\partial t} + \frac{\partial(\rho v)}{\partial r} + \frac{2\rho v}{r} = 0,$$

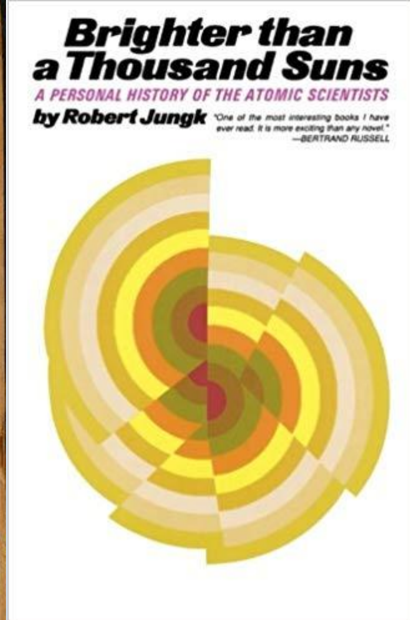
$$\left(\frac{\partial}{\partial t} + v\frac{\partial}{\partial r}\right)\log\frac{p}{\rho^\gamma} = 0.$$

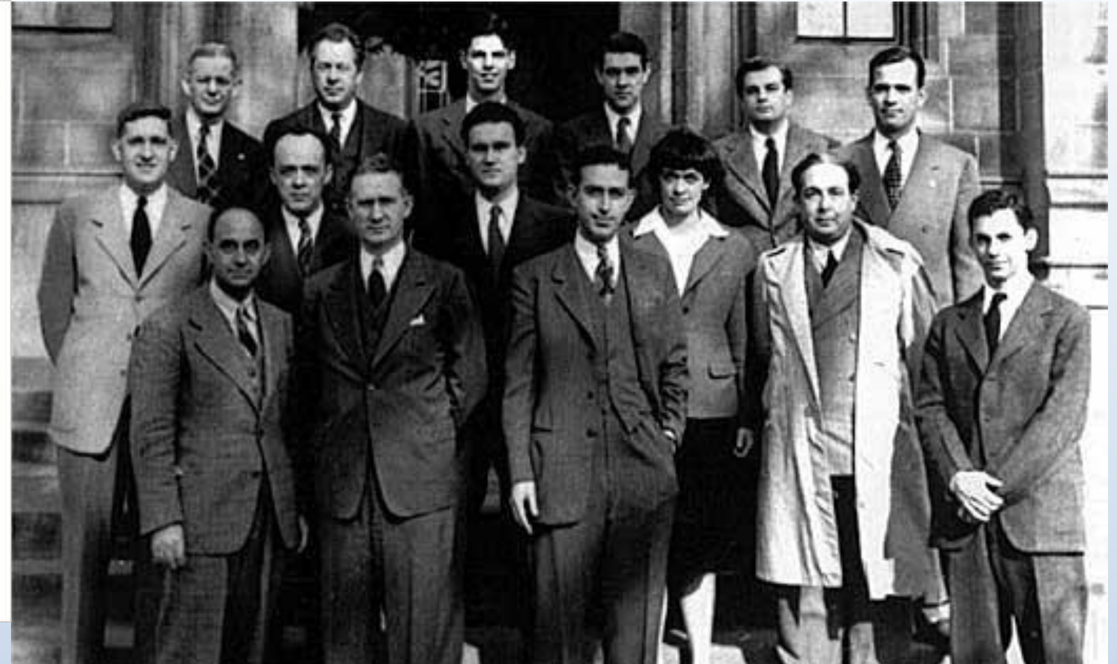
For air ($\gamma = 7/5$), $\beta = 1{\cdot}033$.

L.D.Landau, E.M.Lifshitz,
Fluid Mechanics
§106. A strong explosion.







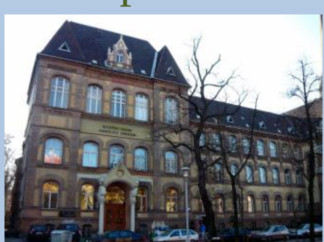


fourth reunion on December 2, 1946. Front row left to right: Enrico Fermi, Walter Zinn, Albert Wattenberg, Leona Marshall and Leo Szilard (both one step back), and Herbert Anderson. Back row second from left: Sam Allison. Photo courtesy US

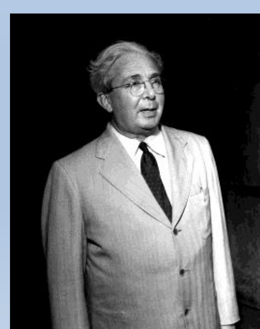
Robert Jungk
Brighter Than a Thousand Suns:
A Personal History of the Atomic Scientists
Grove Press, New York. 1958

The Metallurgical Laboratory scientists. The Metallurgical Laboratory became the first of the national laboratories, the Argonne National Laboratory.

Budapest - Fasori Evangélikus Gimnázium



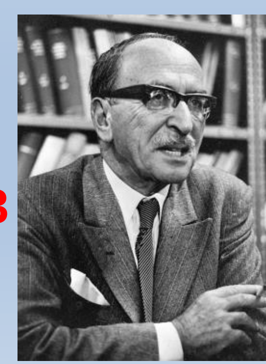
John von Neumann
1903 – 1957



Leó Szilárd
1898 -1964

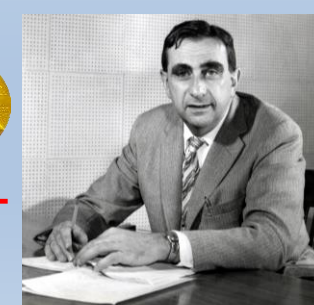
Eugene Wigner
1902-1995

1963



Dennis Gabor
1900-1979

1971



Edward Teller
1908 – 2003

Aleksander Kompaneyets 1914 - 1974

A point explosion in non-uniform atmosphere

Let us assume that the shock wave front is described by equation $f(r, z, t) = 0$. Then a normal component of shock front velocity, D_n, is given by $D_n = \frac{\partial f/\partial t}{|\nabla f|}$. Let the shock front be given in an explicit form by $r = r_s(z, t)$, i.e. $f(r, z, t) = r - r_s(z, t)$, and $\partial f/\partial t = \partial r_s/\partial t$. Therefore, we have for shock wave velocity

$$D_n = \frac{\partial r_s/\partial t}{\sqrt{1 + (\partial r_s/\partial z)^2}}$$

Conservation laws:
L.D.Landau, E.M.Lifshitz Fluid Mechanics

§84. **Surfaces of discontinuity**

mass flux

$[\rho v_x] = \rho_1 v_{1x} - \rho_2 v_{2x} = 0$

momentum flux

$$[p + \rho v_x^2] = 0$$

energy flux

$$\left[\rho v_x\left(\frac{1}{2}v^2 + w\right)\right] = 0$$

From the other side, shock wave velocity can be obtained from the conservation laws of mass, momentum, and energy in the form

$$D_n = \sqrt{\frac{p_1}{\varrho\,(1 - \varrho/\varrho_1)}}$$

Here we assume that a shock wave is strong, i.e. $p_1 \gg p$, where the subscript "1" refers to the shock-compressed gas, while the variables without a subscript correspond to the undisturbed plume. The density ratio across a strong shock equals to

$$\frac{\varrho_1}{\varrho} = \frac{\gamma + 1}{\gamma - 1}$$

Where $\gamma = c_p/c_v$ is the adiabatic index. The pressure p_1 is related to the energy density as $p_1 = (\gamma - 1)\lambda E/V$, where E is the total energy released, V is the volume of the region encompassed by the shock wave, $\lambda = \lambda(\gamma)$ is an empirical factor. We consider $\lambda = const.$

Finally
$$D_n = \sqrt{\frac{(\gamma^2 - 1)\lambda E}{2\varrho V}}$$

Total volume of the region encompassed by the shock wave: $V(t) = \pi \int_{z_1}^{z_2} r_s^2\,(z,t)dz$, where $r_s(z_1,t) = r_s(z_2,t) = 0$. Introduce a new variable $y = y\,(t) = \int_{t_b}^{t} \sqrt{\frac{(\gamma^2-1)\lambda E}{2\varrho_b V(u)}}\,du,$

where t_b is the time instant of the breakdown and $\varrho_b = \varrho(0, z_b, t_b)$ is the initial vapor density at the breakdown point. Finally we find

$$\left(\frac{\partial r_s}{\partial y}\right)^2 = \frac{\rho_b}{\rho(r,z)}\left[1+\left(\frac{\partial r_s}{\partial z}\right)^2\right]$$

Consider first a stationary isothermal atmosphere with exponential density distribution

$$\rho(z) = \varrho_0\, exp(-z/z_0)$$

Assuming t_b =0, z_b =0, $\rho_b = \rho_0$, we have
$$\left(\frac{\partial r_s}{\partial y}\right)^2 - \exp\left(\frac{z}{z_0}\right)\left[1+\left(\frac{\partial r_s}{\partial z}\right)^2\right] = 0$$

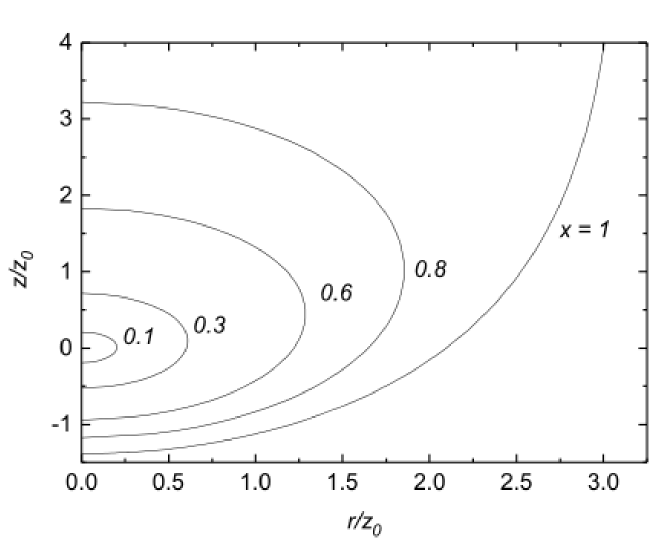
This equation can be solved by the separation of variables *y* and *z*:

$$\left(\frac{\partial r_s}{\partial y}\right)^2 = \xi^2, \quad \exp(z/z_0)\left|1+\left(\frac{\partial r_s}{\partial t}\right)^2\right| = \xi^2$$

Finally

$$r_S = 2z_0 \arccos\left\{\frac{\exp(z/2z_0)}{2}[1 - x^2 + \exp(z/z_0)]\right\}$$

where $x = y / 2\, z_0$.



For arbitrary density distribution $\rho\ (z)$ the solution is given by:

$$r_S = \pm\left(\xi\, y + \int_{z_b}^{z} du \sqrt{\xi^2 \rho(u)/\rho_b - 1}\right)$$

$$y = -\xi \int_{z_b}^{z} du \frac{\rho(u)/\rho_b}{\sqrt{\xi^2 \rho(u)/\rho_b - 1}}$$

B. S. Luk'yanchuk, S. I. Anisimov, *Propagation of shock wave generated by optical breakdown in a laser produced plume*, Proc. SPIE 5448, 95-102 (2004)

Gas dynamic equations (expansion into vacuum):

$$\frac{\partial \rho}{\partial t} + div(\rho \mathbf{u}) = 0$$

Eq. of continuity

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\nabla)\mathbf{u} = -\frac{\nabla p}{\rho}$$

Euler equation

$$\frac{\partial S}{\partial t} + (\mathbf{u}\nabla)S = 0$$

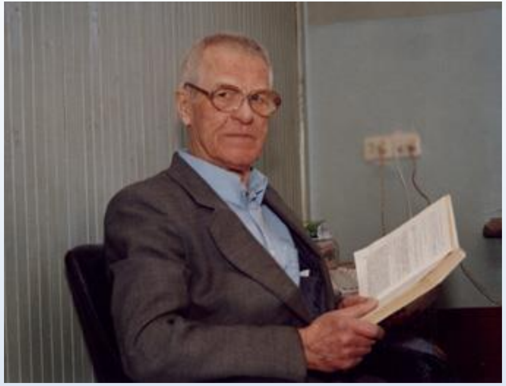
Entropy conservation

$$\varepsilon = \frac{1}{\gamma - 1}\frac{p}{\rho}, \quad S = \frac{1}{\gamma - 1}\ln\left(\frac{p}{\rho^{\gamma}}\right)$$

Eq. of State (Ideal gas)

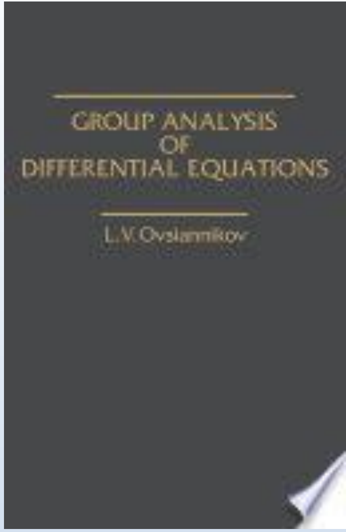
$$\boldsymbol{\gamma = c_p / c_v}$$

Sophus Lie
1842 – 1899



Lev Ovsiannikov
1919 -2014

L.V. Ovsiannikov,
Group Analysis of Differential Equations
Academic, New York (1982)

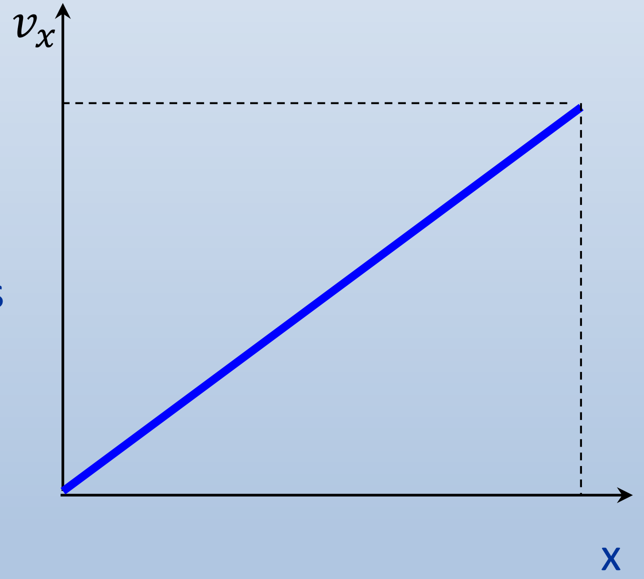


Particular solutions of gas-dynamic Eqns.
(Lie group theory)

$$r_i(t) = \sum_k F_{ik}(t)\, r_k(0)$$

$$F_{ik} = \begin{pmatrix} \frac{X(t)}{X_0} & 0 & 0 \\ 0 & \frac{Y(t)}{Y_0} & 0 \\ 0 & 0 & \frac{Z(t)}{Z_0} \end{pmatrix}$$

Linear profile of the velocities



$$v_x = x\frac{dX/dt}{X} \qquad v_y = y\frac{dY/dt}{Y} \qquad v_z = z\frac{dZ/dt}{Z}$$

Initial profiles for isentropic plume

$$p(\mathbf{r},t) = \frac{E}{I_2(\gamma)XYZ}\left[\frac{X_0Y_0Z_0}{XYZ}\right]^{\gamma-1}\left[1-\frac{x^2}{X^2}-\frac{y^2}{Y^2}-\frac{z^2}{Z^2}\right]^{\frac{\gamma}{\gamma-1}}$$

$$\rho(\mathbf{r},t) = \frac{M}{I_1(\gamma)XYZ}\left[1-\frac{x^2}{X^2}-\frac{y^2}{Y^2}-\frac{z^2}{Z^2}\right]^{\frac{1}{\gamma-1}}$$

$$M = \int_V \rho\, dx\, dy\, dz \qquad E = \frac{2\pi}{\gamma-1}\int_{V_0} p\, dx\, dy\, dz$$

Anisimov S. I., Bäuerle D., Luk'yanchuk B. S.
Gas Dynamics and Film Profiles in Pulsed-Laser Deposition of Materials, Phys. Rev. B **48**, 12076 (1993)

Equations of motion

$$\ddot{X} = -\frac{\partial U}{\partial X}, \quad \ddot{Y} = -\frac{\partial U}{\partial Y}, \quad \ddot{Z} = -\frac{\partial U}{\partial Z} \qquad U = \frac{(5\gamma-3)}{(\gamma-1)}\frac{E}{M}\left[\frac{X_0 Y_0 Z_0}{XYZ}\right]^{\gamma-1}$$

Initial conditions:

$$X(0) = X_0, \quad Y(0) = Y_0, \quad Z(0) = Z_0,$$
$$\dot{X}(0) = \dot{Y}(0) = \dot{Z}(0) = 0.$$

The dimensionless variables

$$\xi = \frac{X}{X_0}, \quad \eta = \frac{Y}{X_0}, \quad \zeta = \frac{Z}{X_0}, \quad \tau = \frac{t\beta^{1/2}}{X_0},$$
$$\eta_0 = \frac{Y_0}{X_0}, \quad \zeta_0 = \frac{Z_0}{X_0}, \quad \beta = (5\gamma - 3)\frac{E}{M}.$$

The dimensionless equations of motion

$$\xi\ddot{\xi} = \eta\ddot{\eta} = \zeta\ddot{\zeta} = \left(\frac{\eta_0\zeta_0}{\xi\eta\zeta}\right)^{\gamma-1},$$
$$\xi(0) = 1, \quad \eta(0) = \eta_0, \quad \zeta(0) = \zeta_0,$$
$$\dot{\xi}(0) = \dot{\eta}(0) = \dot{\zeta}(0) = 0.$$

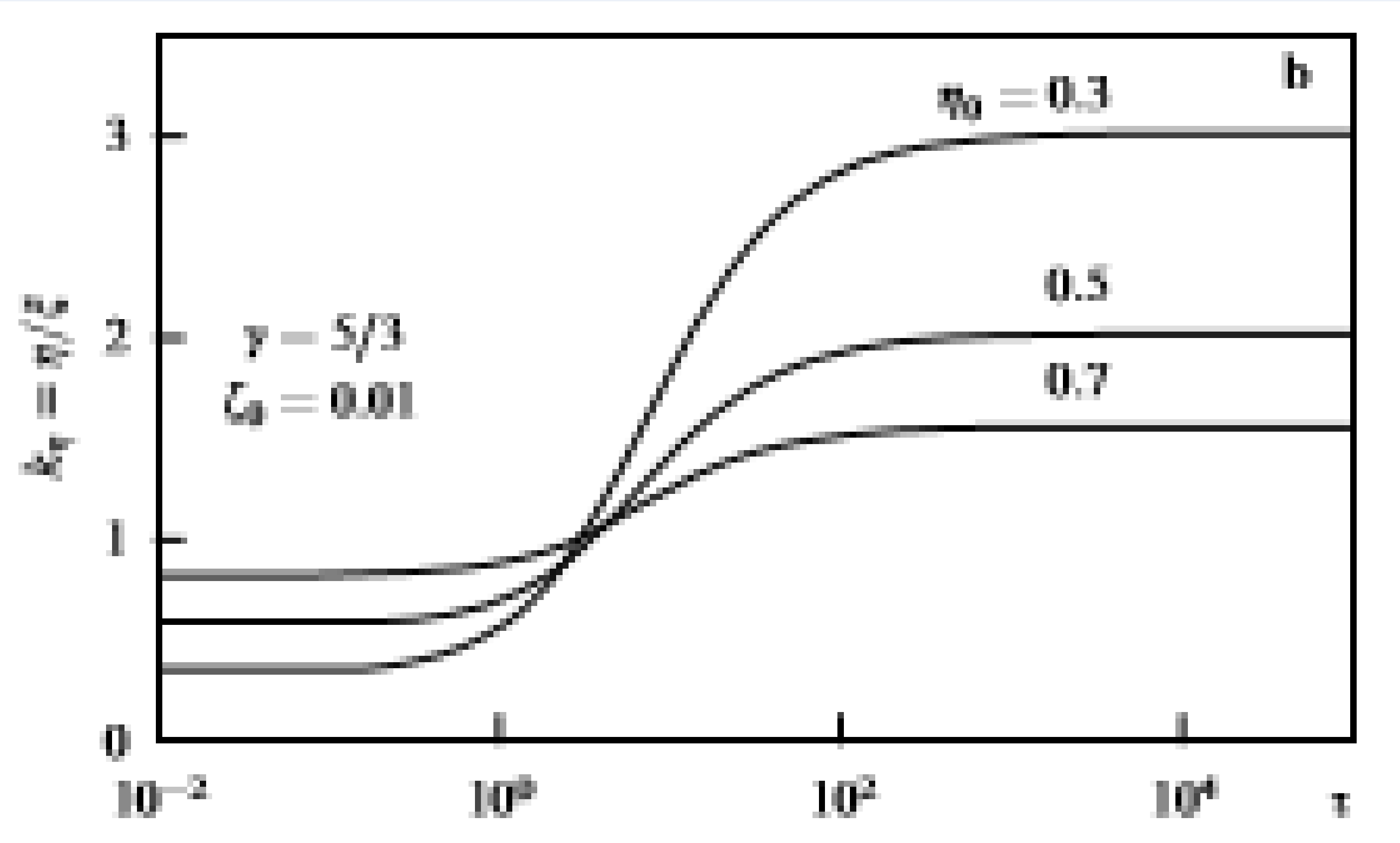
$$\Rightarrow \quad \frac{1}{2}(\dot{\xi}^2 + \dot{\eta}^2 + \dot{\zeta}^2) + \frac{U(\tau)}{\beta} = \varepsilon = \text{const},$$

where $\varepsilon = \frac{1}{\gamma-1}$.

when $\gamma = 5/3$ there is an additional integral

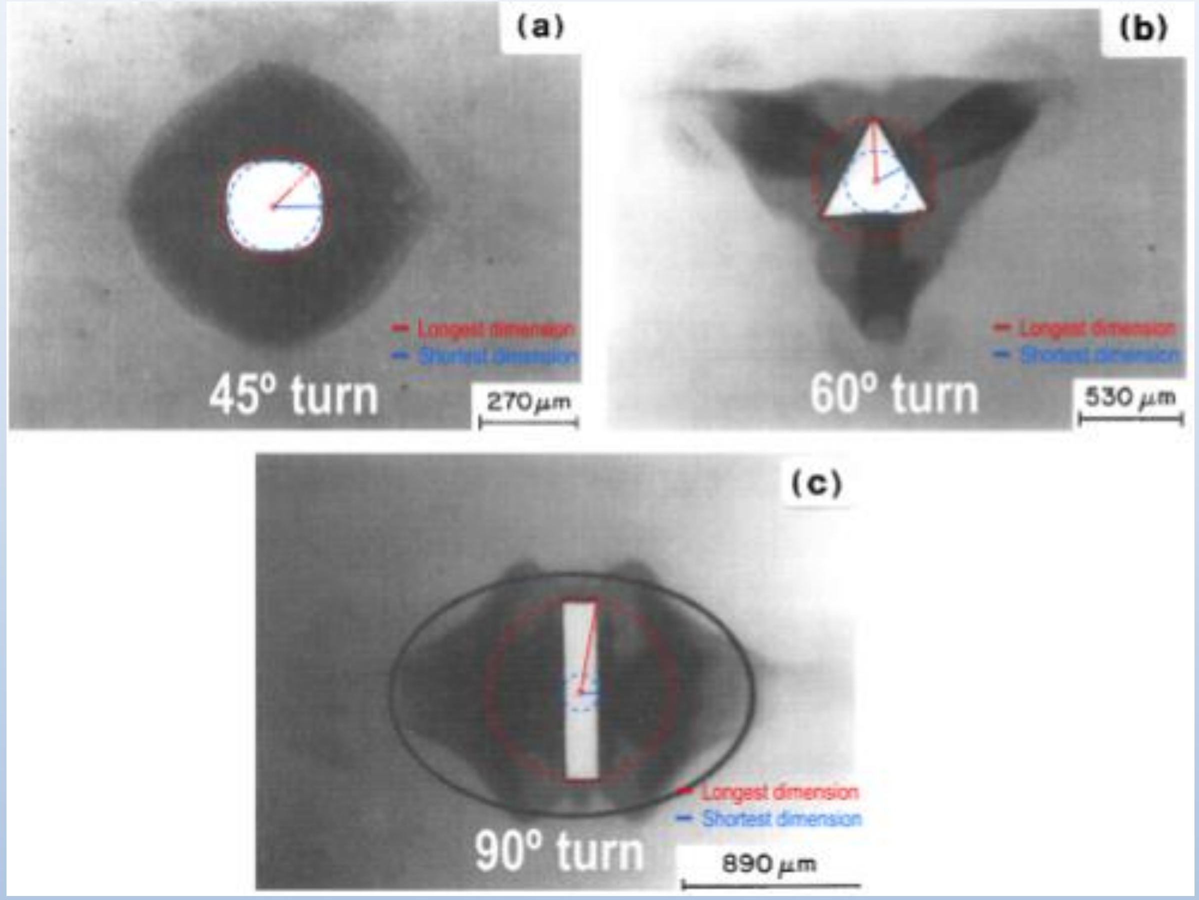
$$\xi^2 + \eta^2 + \zeta^2 = 3\tau^2 + 1 + \eta_0^2 + \zeta_0^2.$$

Results of integration



The spot deposited is found to be as if rotated through an angle of 90° relative to the focal spot. This experimentally discovered phenomenon has come to be known as the `flip-over effect'. Clearly, the same rotation effect should be observable for a focal spot of any shape possessing an nth-order axis of rotation Cn. In this case, the angle of rotation is 180 ° /n.

Flip over effect in pulsed laser deposition



The flip-over effect in pulsed laser deposition: Is it relevant at high background gas pressures?

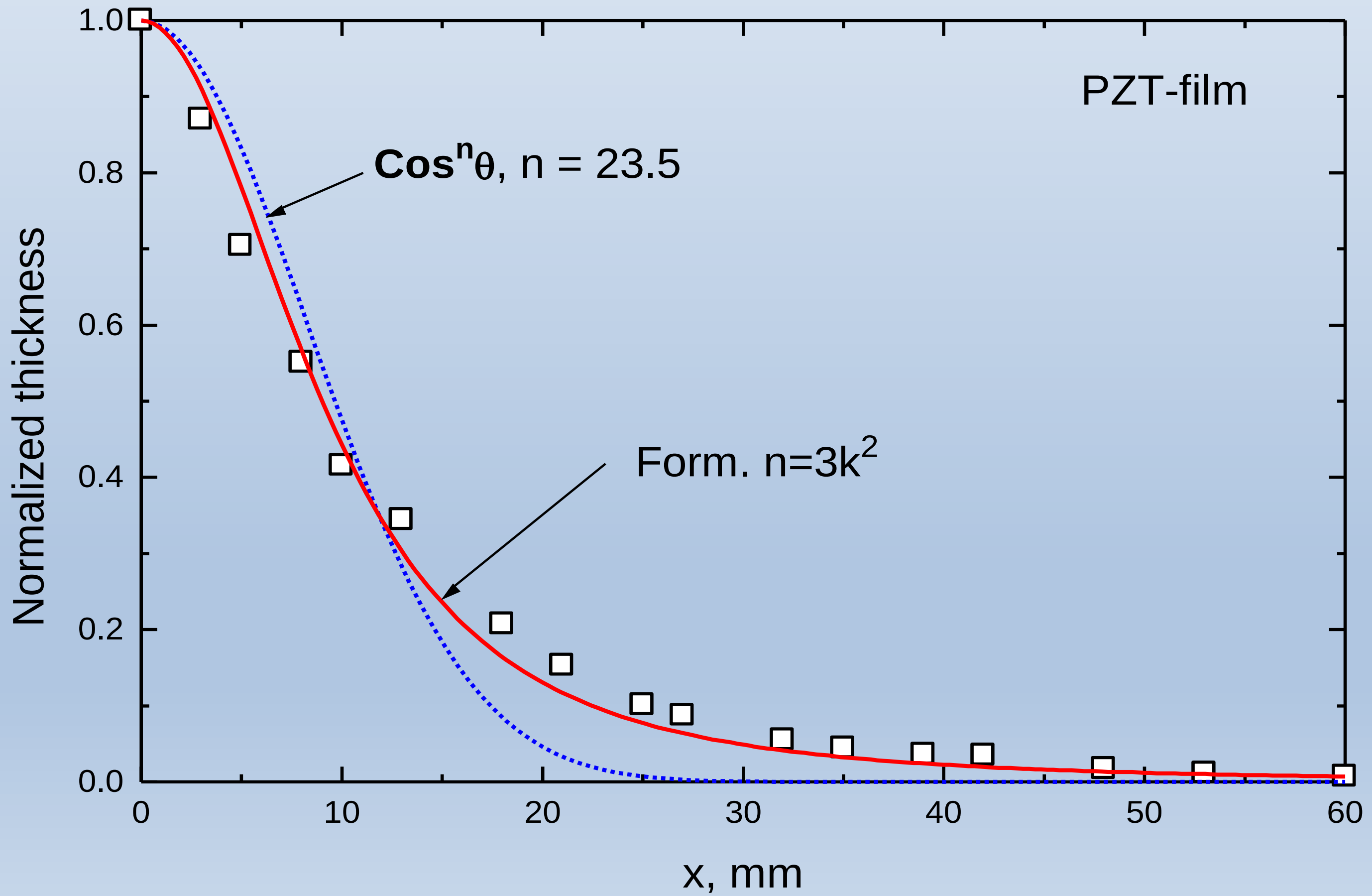
Alejandro Ojeda-G-P[a], Christof W. Schneider[a,*], Max Döbeli[b], Thomas Lippert[a], Alexander Wokaun[a]

Applied Surface Science 357 (2015) 2055–2062

Film thickness profile

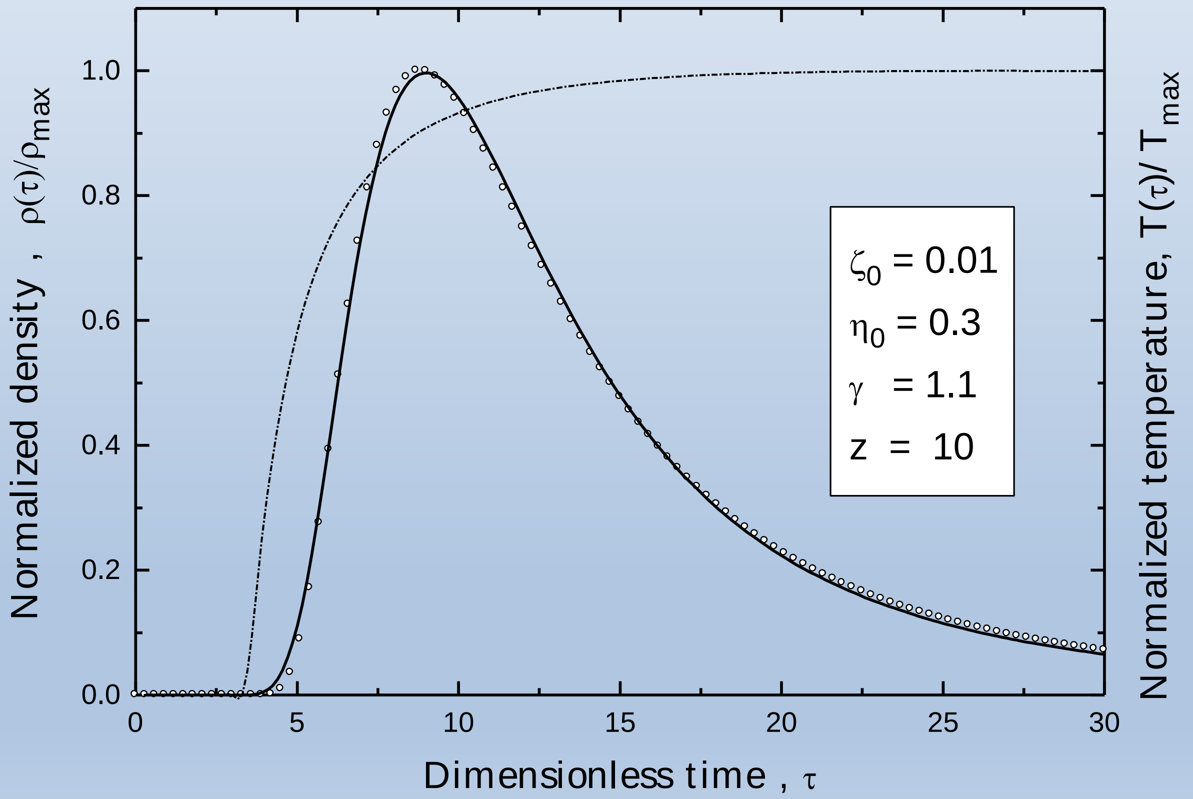
$$h(\theta_x,\theta_y)=\frac{Mpq^2}{2\pi\rho_s z_s^{\ 2}}\left[p+tg^2\theta_x+q^2tg^2\theta_y\right]^{-3/2}$$

M.Tyunina, K.Sreenivas, C.Björmander, K.V.Rao, 1995

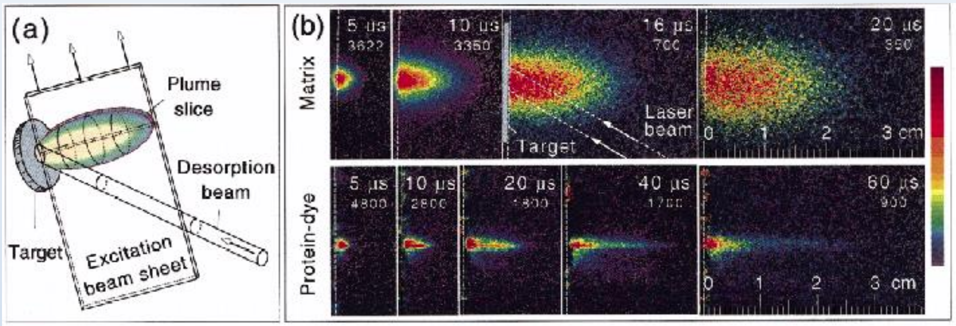


Time-of-flight spectra

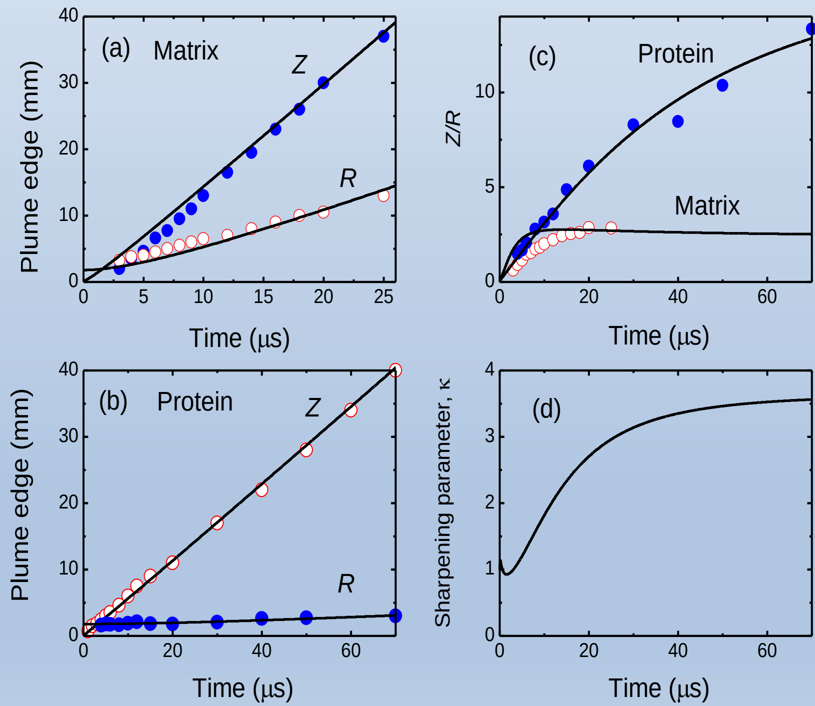
$$\rho_m(\tau) = \frac{A}{\tau^3} \exp\left[-B(\frac{z}{\tau} - u)^2 \right]$$

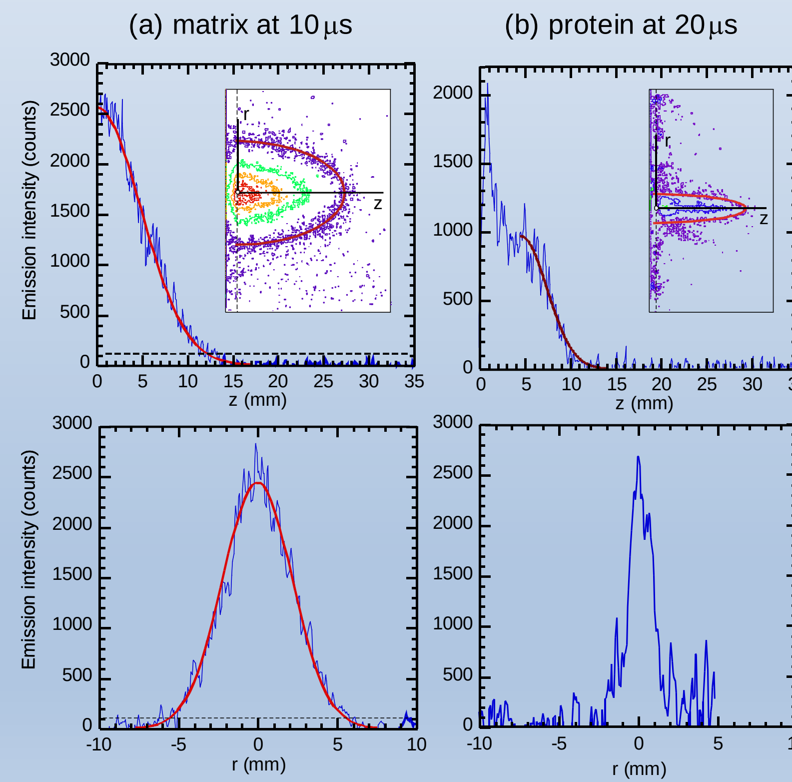


Multicomponent plume



Puretzky A. A., Geohegan D.B., Hurst G. B., Buchanan M. V., Luk'yanchuk B. S.
Imaging of Vapor Plumes Produced by Matrix Assisted Laser Desorption: Plume Sharpening Effect
Physical Review Letters, vol. **83**, Number 2, pp. 444-447 (1999)



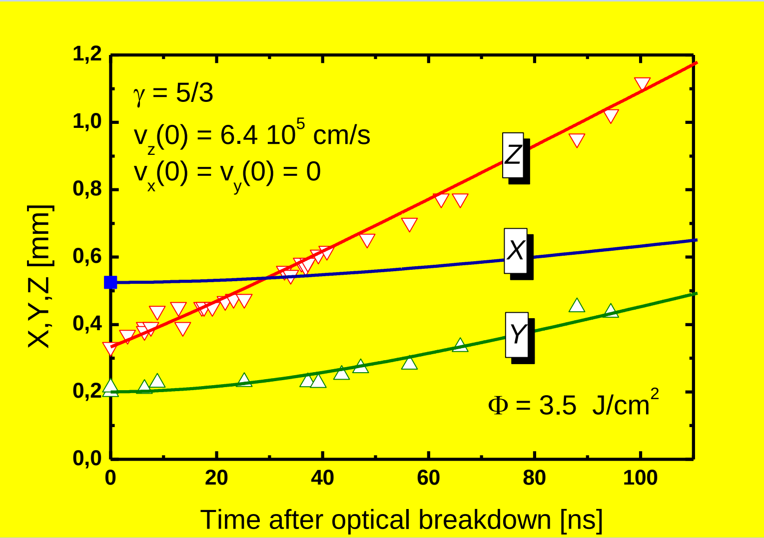


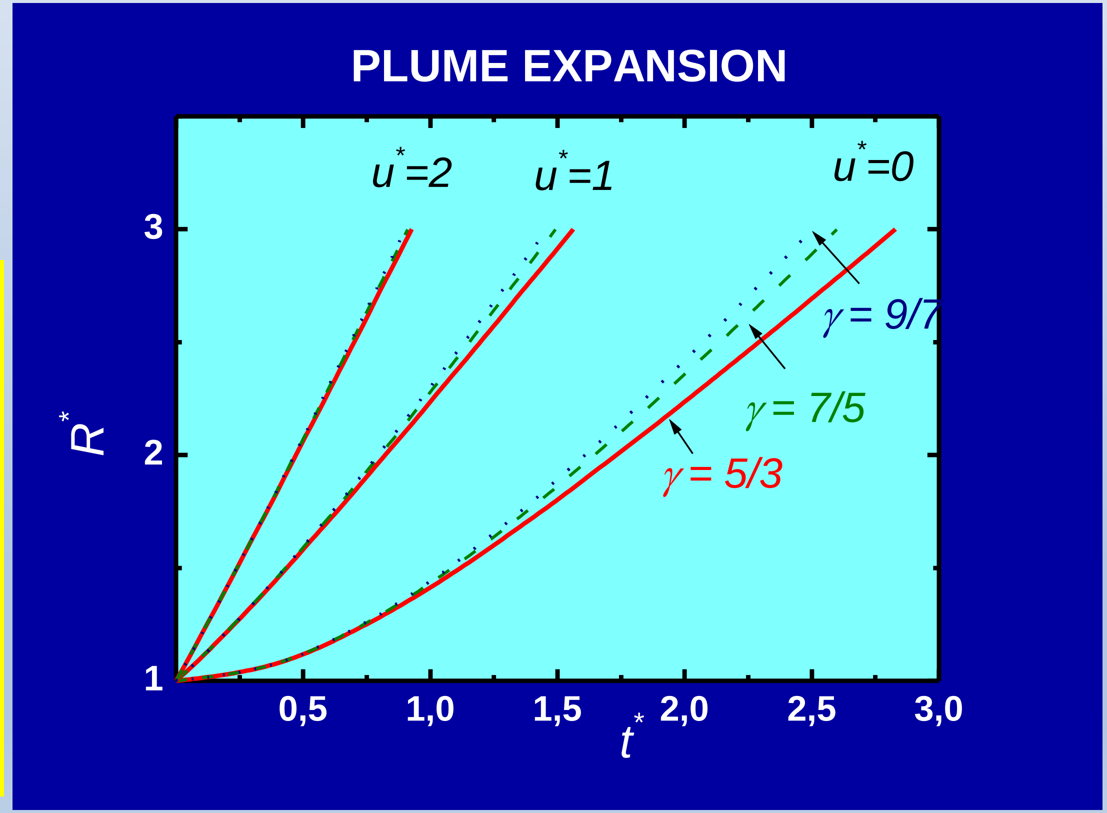
Expansion of the spherical plume

$$\tilde{t} = \left[\tilde{u}^2 + \frac{2}{3(\gamma-1)}\right]^{-\frac{1}{2}} \left\{ \tilde{R}\ {}_2F_1\left[a,b;c;\frac{\tilde{R}^{-3(\gamma-1)}}{1+\frac{3}{2}(\gamma-1)\tilde{u}^2}\right] - {}_2F_1\left[a,b;c;\frac{1}{1+\frac{3}{2}(\gamma-1)\tilde{u}^2}\right]\right\}$$

$$\gamma = c_p / c_v = 5/3$$

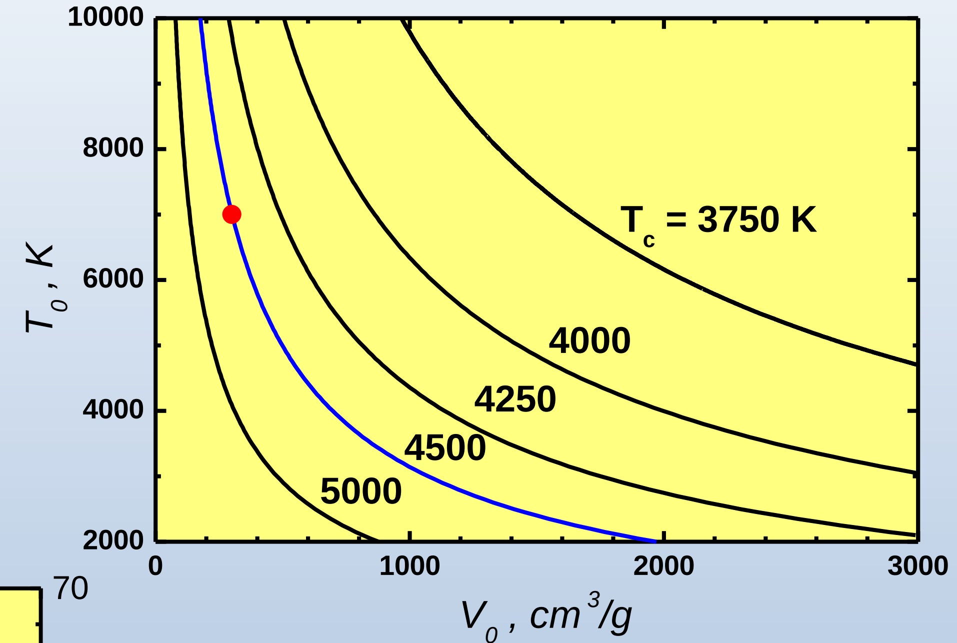
$$\left(\frac{R}{R_0}\right)^2 \equiv \Psi(t) = 1 + 2\frac{u_0}{R_0}t + \left[\left(\frac{u_0}{R_0}\right)^2 + \frac{16}{3}\frac{E}{MR_0^2}\right]t^2$$



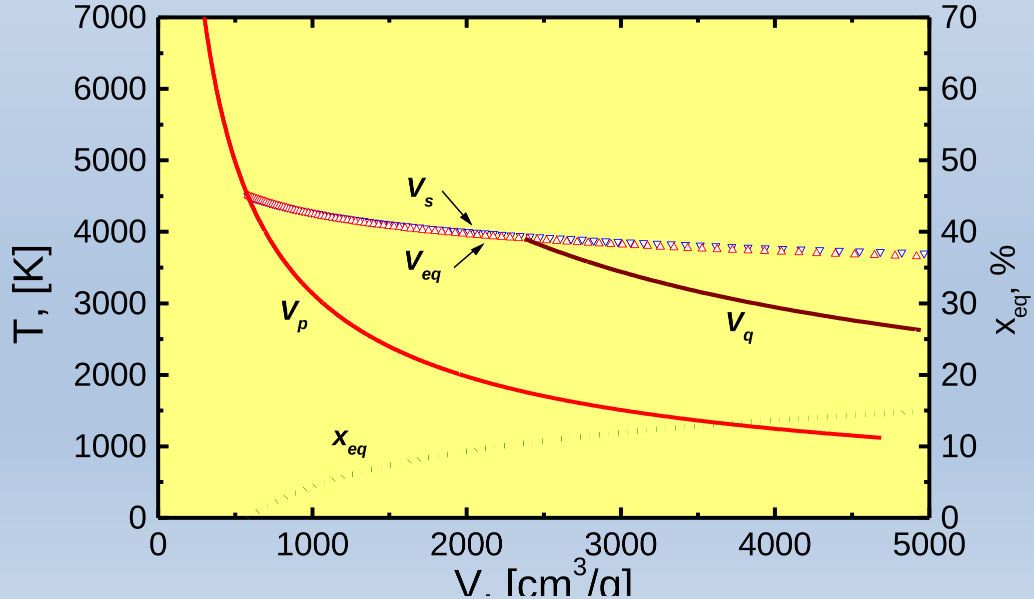


Kinetics of condensation

- Entering into the condensation region:
- Poisson adiabatic is crossing the saturated vapour curve, given by Clapeyron-Clausius equation



Raizer Theory



$$V = V_0 \left[\frac{T}{T_0} \right]^{-3/2}$$

$$V = B \left(\frac{T}{T_s} \right)^{3/2} \cdot exp \left[\frac{q}{T} \right]$$

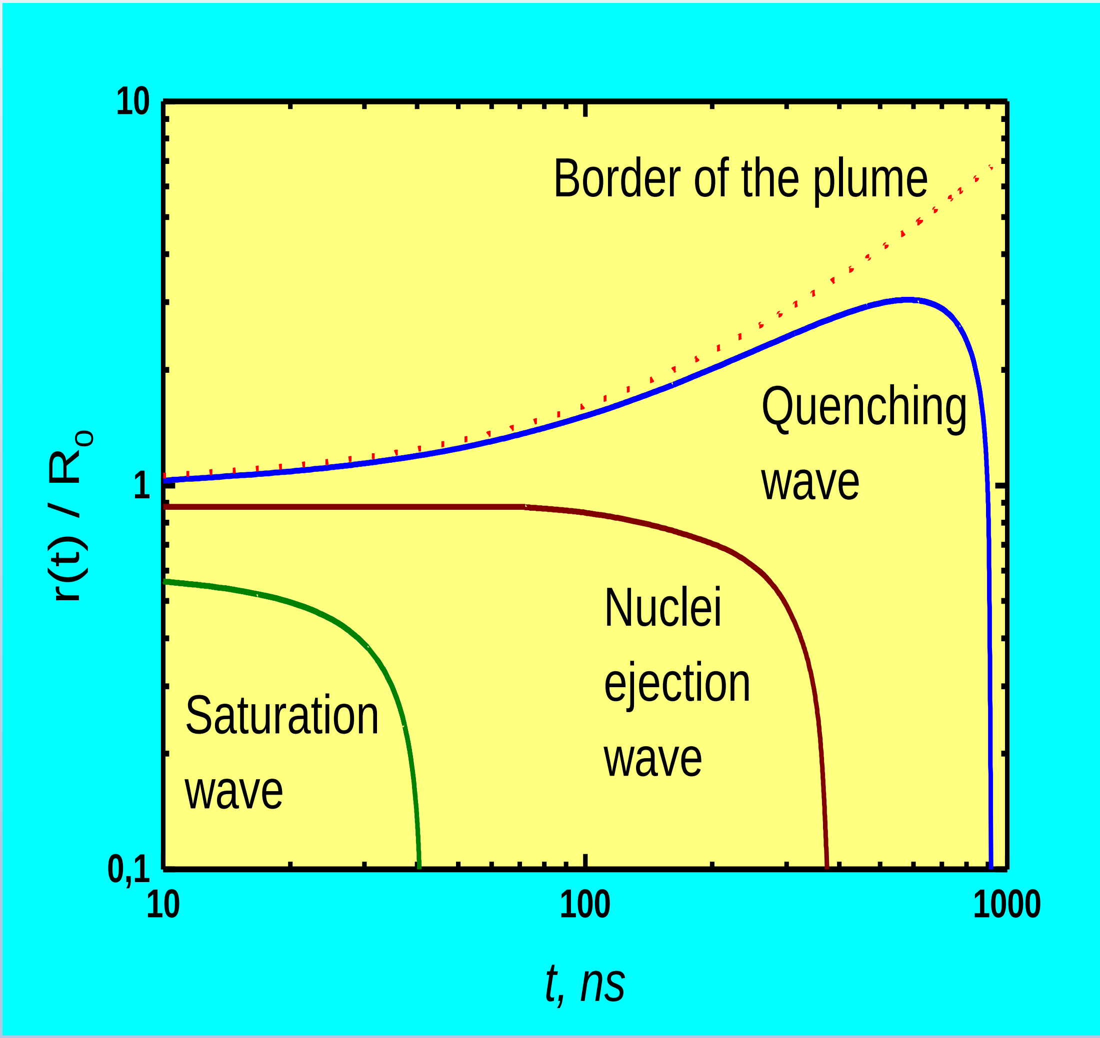
Characteristic waves inside the plume

- The saturation wave
- The quenching wave
- The nuclei ejection

$$\frac{r_c(t)}{R(t)} = \sqrt{1 - \frac{T_c}{T_0}\Psi(t)}$$

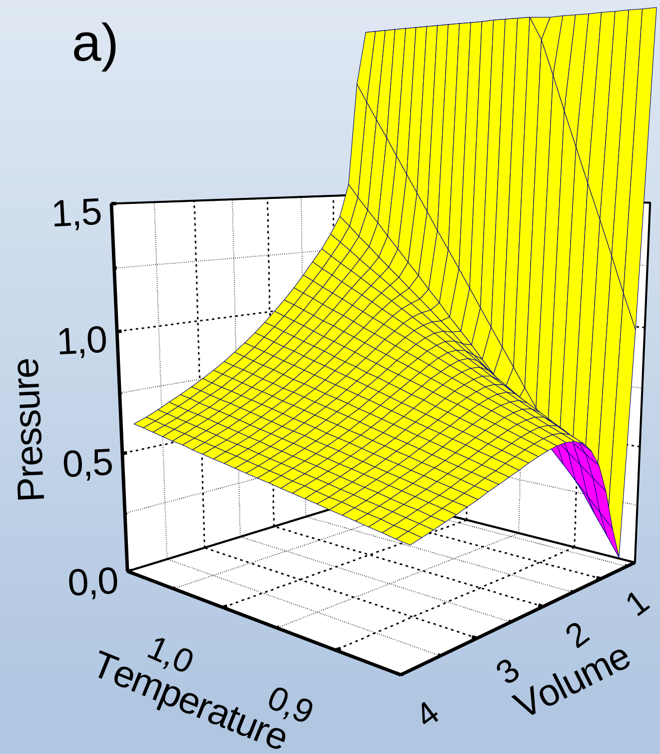
$$\frac{r_q}{R} = \sqrt{1 - \left(t_k \Psi \frac{d\Psi}{dt}\right)^{1/2}}$$

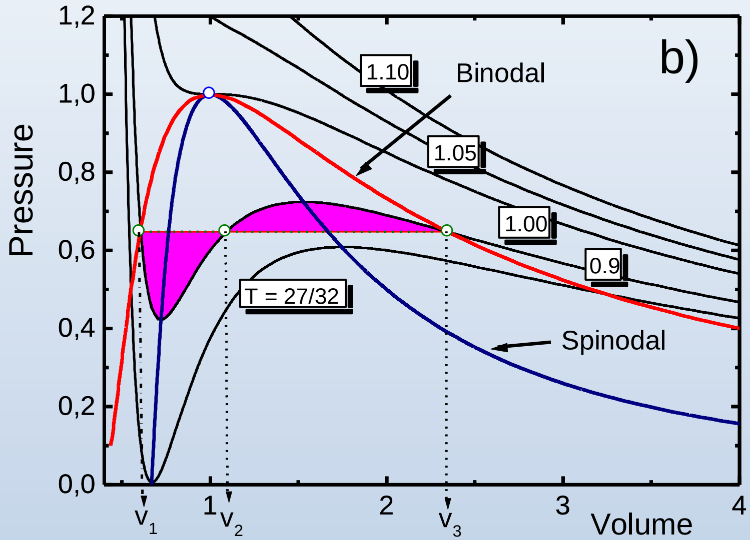
$$\frac{1}{T_{eq}}\frac{dT_{eq}}{dt} = -\frac{1}{\Psi}\frac{d\Psi}{dt} + \left[\frac{2}{3}\frac{q}{T_p} - 1\right]\left(\frac{\alpha}{\theta_p}\right)^3 \frac{d\nu}{dt}$$

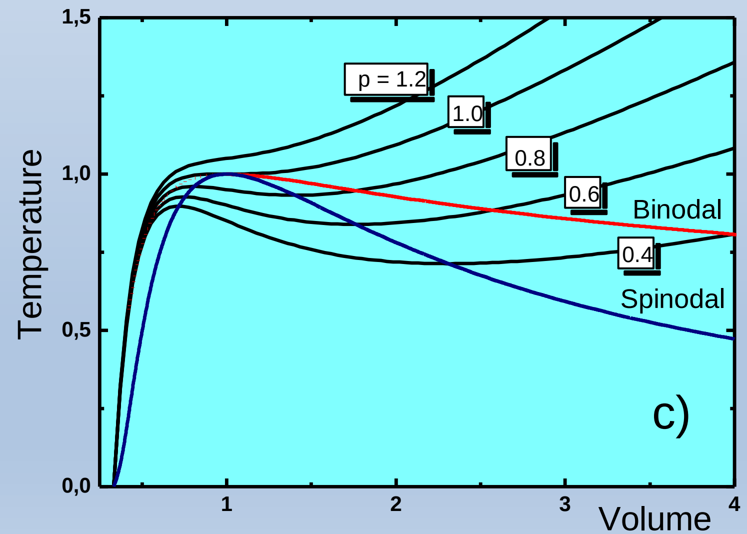


The condensation process is governed by supercooling

$$\theta = \frac{T_{eq} - T}{T_{eq}}$$



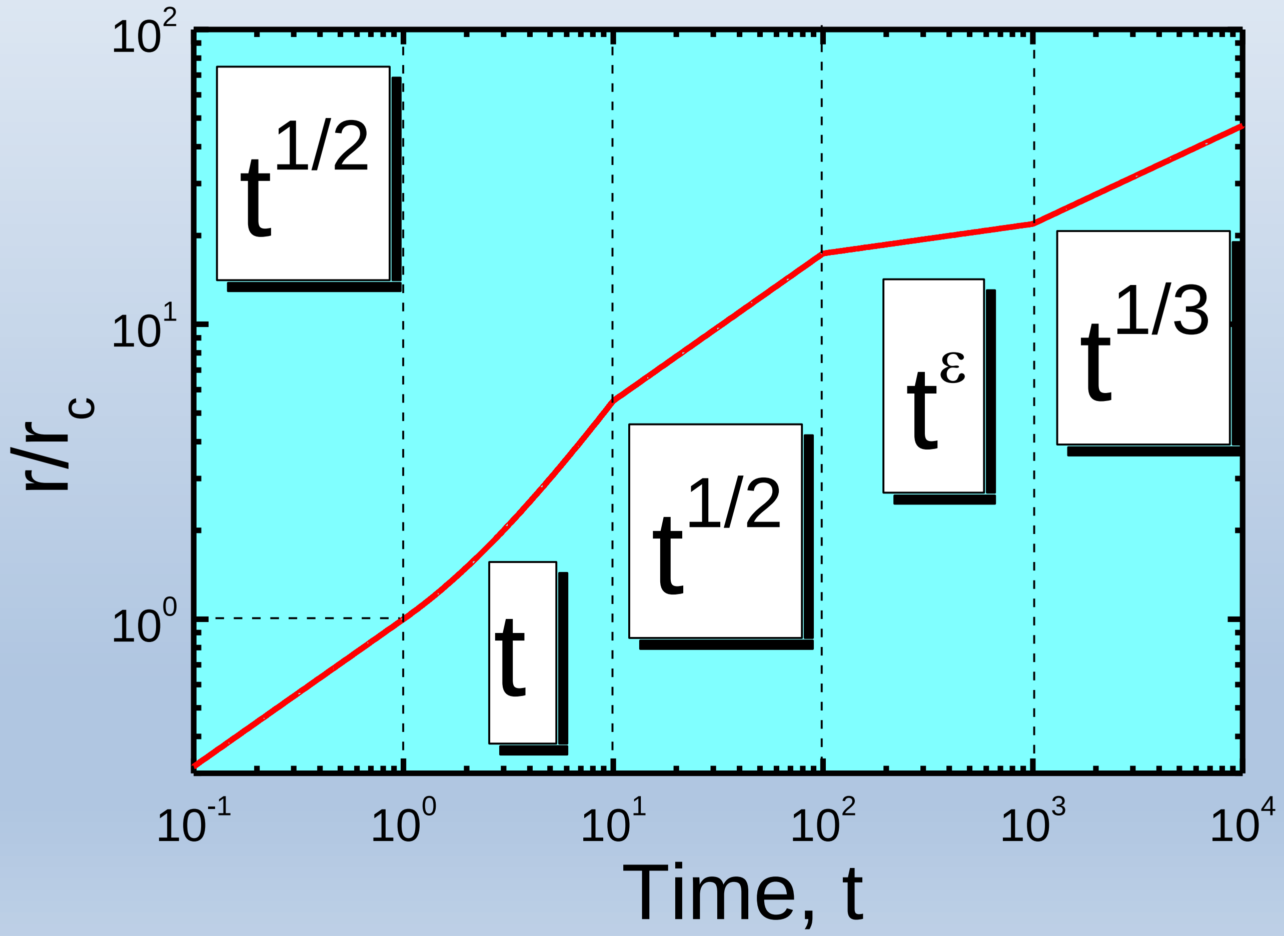




The nucleation theory

$$\frac{\partial f}{\partial t} = -\frac{\partial J}{\partial g}, \quad J = -D_s \frac{\partial f}{\partial g} + B_s\, f$$

$$\frac{d\nu}{dt} = k_\nu \exp\left[-\frac{T_\nu}{T}\frac{1}{\theta^2}\right]$$



Zeldovich-Raizer Theory

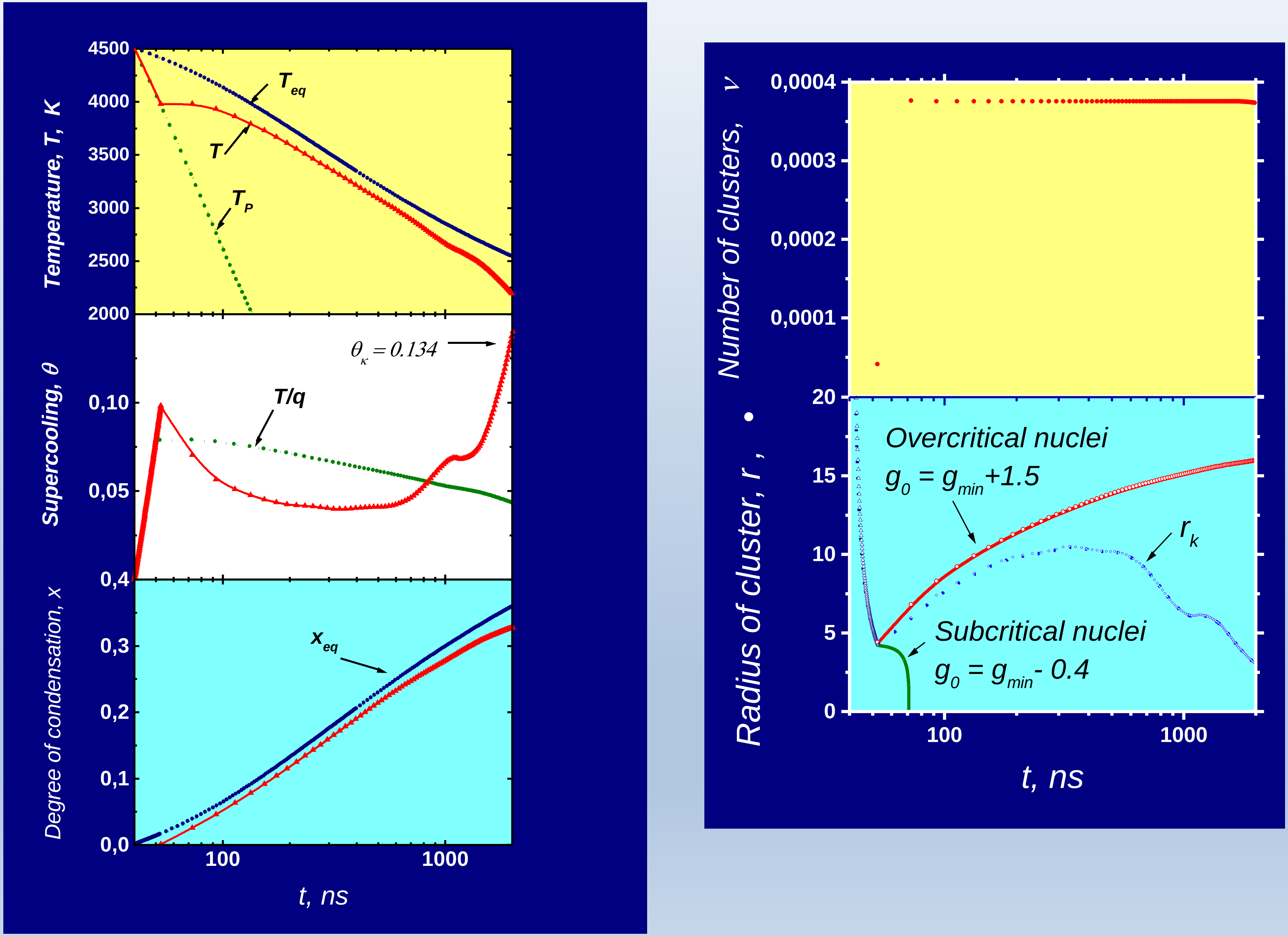
$$(1+x)\frac{dT}{dt} + (1-x)\frac{T}{\Psi}\frac{d\Psi}{dt} = \left(\frac{2}{3}q - T\right)\frac{dx}{dt}$$

$$\frac{dx}{dt} = g\frac{d\nu}{dt} + \nu\frac{dg}{dt}$$

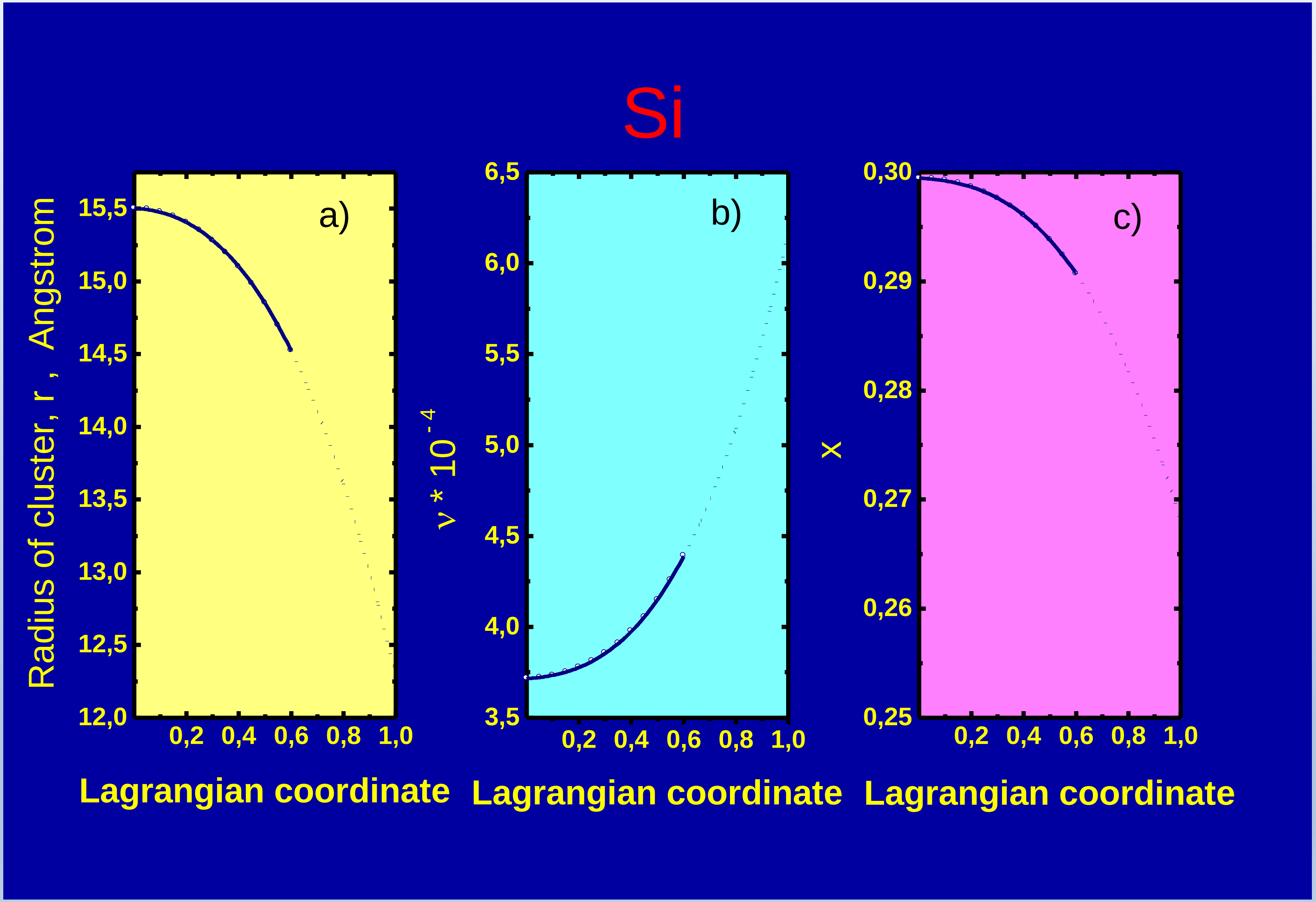
$$\frac{d\nu}{dt} = k_{\nu 0}(1-x)\left(1-\xi^2\right)^{3/2}\Psi^{-3/2}\exp\left[-\frac{T_\nu}{T}\frac{1}{\theta^2}\right]$$

$$\frac{dg}{dt} = k_g g^{2/3}\sqrt{T}(1-x)\left(1-\xi^2\right)^{3/2}\Psi^{-3/2}\left\{1-\exp\left[-\frac{q}{T}\left(\theta - \alpha g^{-1/3}\right)\right]\right\}$$

Dynamics of nucleation and cluster growth

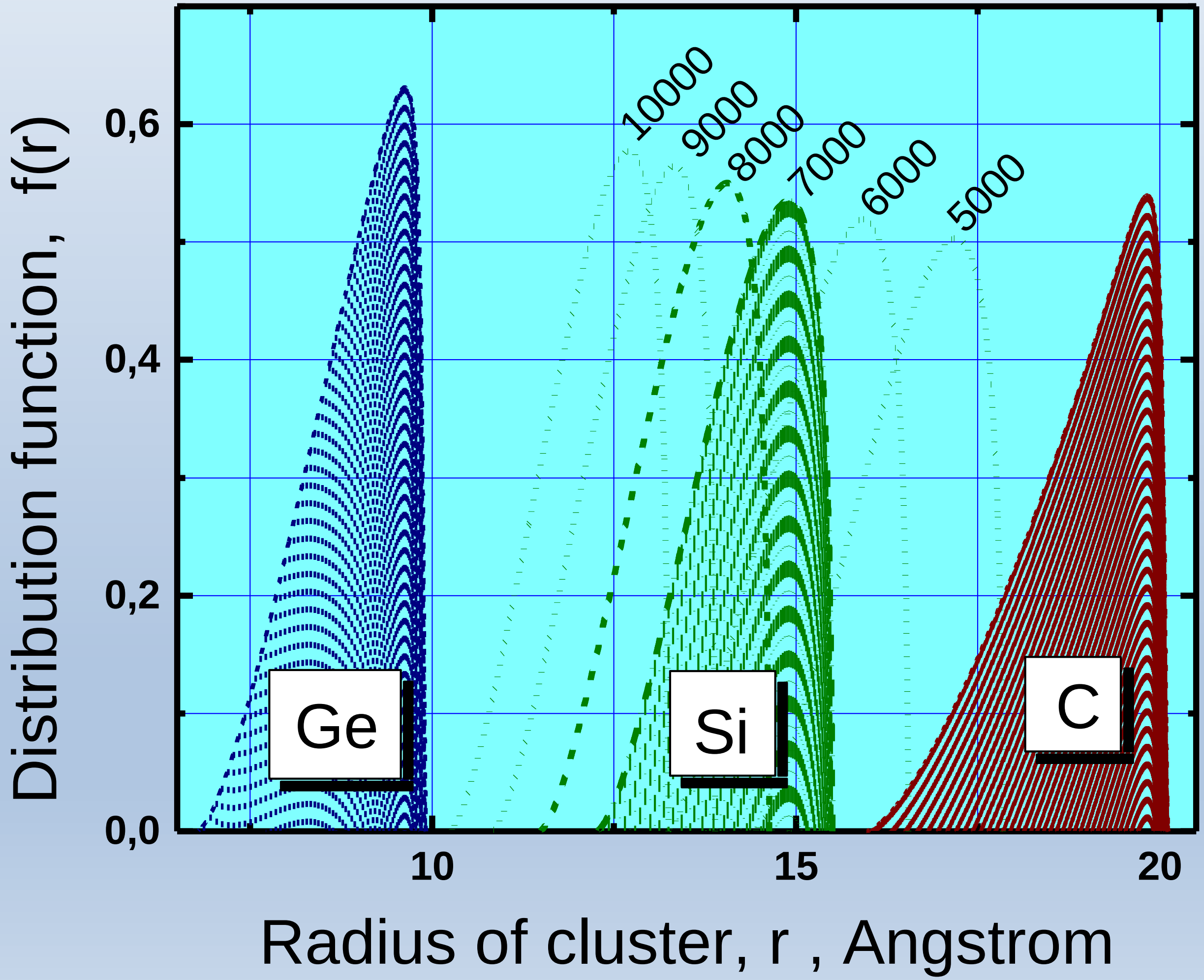


Nucleation versus Lagrangian coordinate

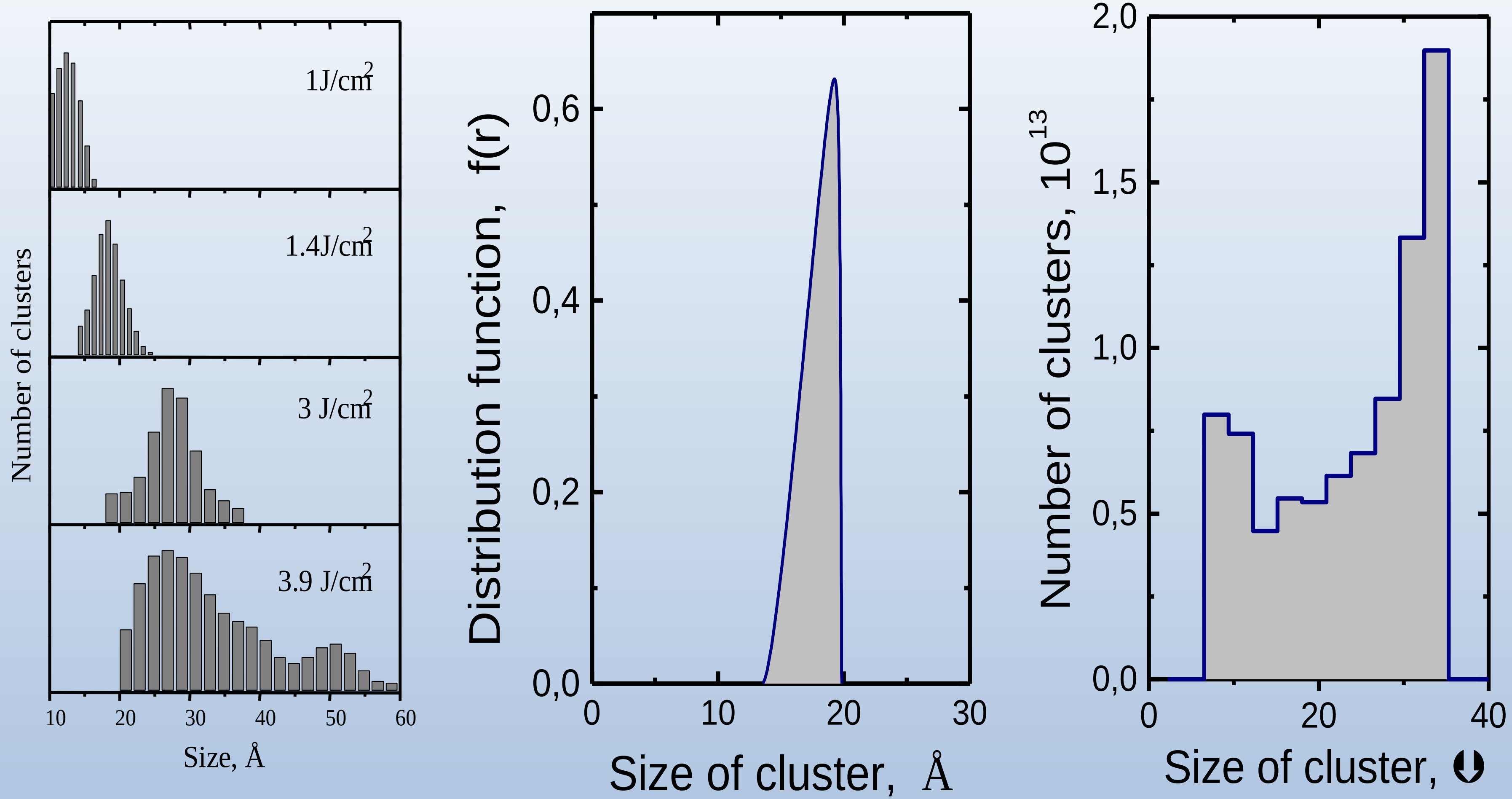


The distribution function

$$F(r) = -\frac{dN}{dr} = -\frac{32}{\pi}\frac{M}{m}\frac{\nu(\xi)\xi^2\left(1-\xi^2\right)^{3/2}}{dr/d\xi}$$



The role of initial pressure and density profiles



Kuwata M., Luk'yanchuk B., Yabe T.
Nanoclusters formation within the vapor plume, produced by ns-laser ablation: Effect of the initial density and pressure distributions.
Japanese Journal of Applied Physics - Part 1, vol. **40**, Issue 6A, pp. 4262-4268 (2001)

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Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena,
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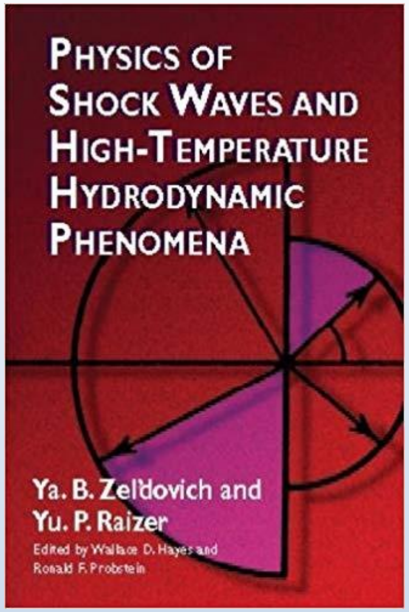

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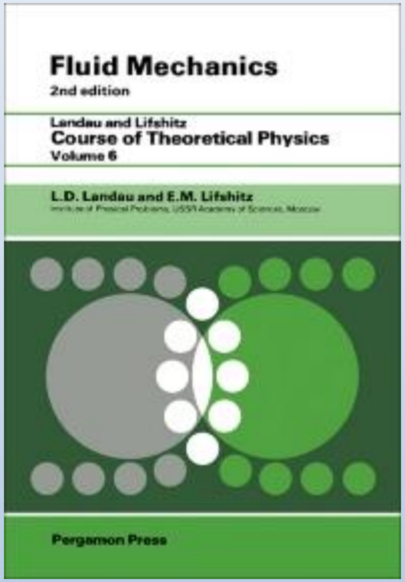

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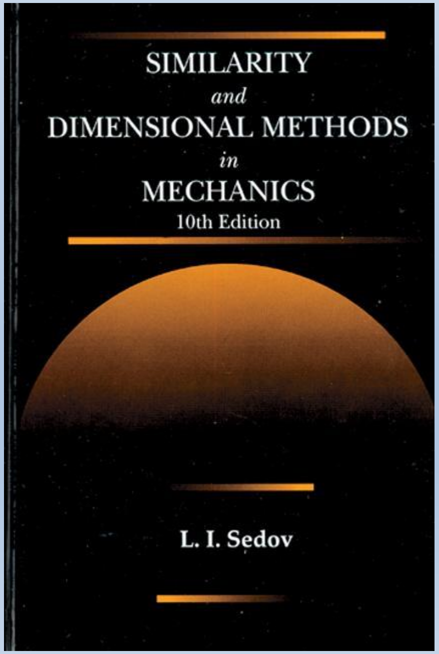

Home work
Read the paper:

N. Arnold, J. Gruber, J. Heitz
Spherical expansion of the vapor plume into ambient gas: an analytical model
Appl. Phys. A **69** [Suppl.], pp. S87–S93 (1999)

A simplified model of plume expansion into ambient atmosphere is presented which is based on the laws of mass, momentum, and energy conservation. In the course of expansion, the energy is redistributed between the thermal and kinetic energies of the plume and (internal and external) shock waves (SW). The expansion is described by ordinary differential equations for the characteristic radii (contact surface, position of the SWs).