

Máster Universitario en Ingeniería Aeronáutica

The Space Environment

Hydrodynamic description of plasmas. Energy transport equations



POLITÉCNICA

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Energy transport equation

The equation for the transport of internal energy $e_{i\alpha}$ is transport without the terms involving $\mathbf{\Pi}_\alpha$ is,

$$\left[\frac{\partial e_{i\alpha}}{\partial t} + \nabla \cdot (e_{i\alpha} \mathbf{u}_\alpha) \right] + (e_{i\alpha} + p_\alpha)(\nabla \cdot \mathbf{u}_\alpha) = -\nabla \cdot \mathbf{q}_\alpha + Q_\alpha - \mathbf{R}_\alpha \cdot \mathbf{u}_\alpha + \underbrace{\left(\frac{m_\alpha u_\alpha^2}{2} \right)}_{\text{Kinetic energy associated to creation/loss of particles}} (S_\alpha - L_\alpha) + \mathbf{J}_\alpha \cdot \mathbf{E}$$

$\mathbf{q}_\alpha = -\kappa_T \nabla T_\alpha$ Heat flow

The term Q_α accounts for the energy transformed in inelastic collision for the ionization we have $Q_I = E_I \nu_I$
Work of friction forces
Kinetic energy associated to creation/loss of particles
Work of the electric field

Using the LTE approximation this equation can be expressed in terms of the temperature $T_\alpha(\mathbf{r}, t)$ and/or the scalar pressure $p_\alpha(\mathbf{r}, t)$ since,

$$e_i = \frac{3}{2} n_\alpha k_B T_\alpha \quad \text{or} \quad e_i = \frac{3}{2} p_\alpha$$

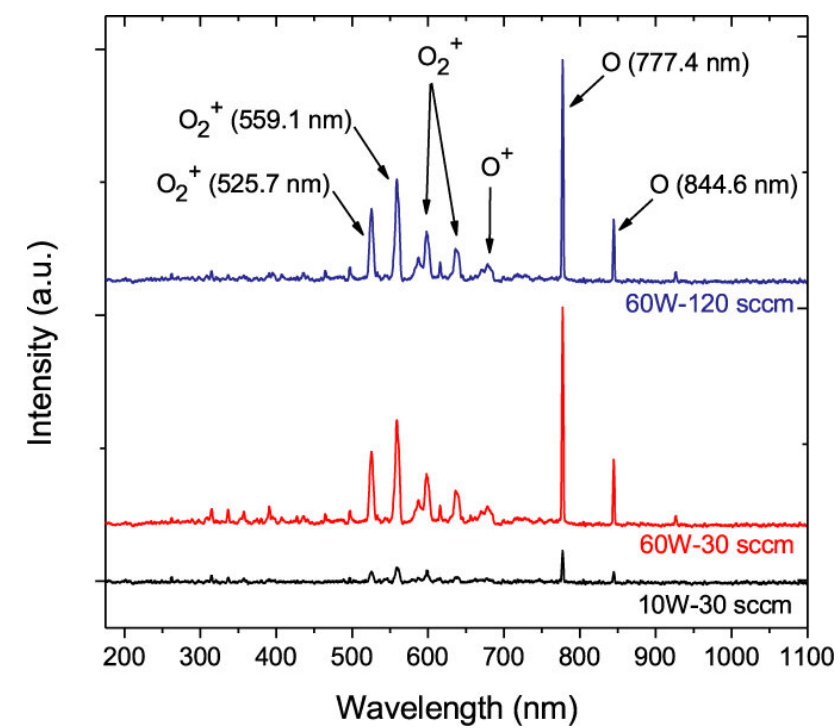
$$\frac{3}{2} \frac{Dp_\alpha}{Dt} + \frac{5}{2} p_\alpha (\nabla \cdot \mathbf{u}_\alpha) = -\nabla \cdot \mathbf{q}_\alpha - \mathbf{R}_\alpha \cdot \mathbf{u}_\alpha + Q_\alpha + \left(\frac{m_\alpha u_\alpha^2}{2} \right) (S_\alpha - L_\alpha) + \mathbf{J}_\alpha \cdot \mathbf{E}$$

Other terms: Absorption and emission of radiation

Collision processes emit radiation: recombination, excitation, de-excitation...

These compose the radiation spectra from plasmas, and also stars.

This is seen as an energy **sink** in the transport equation.

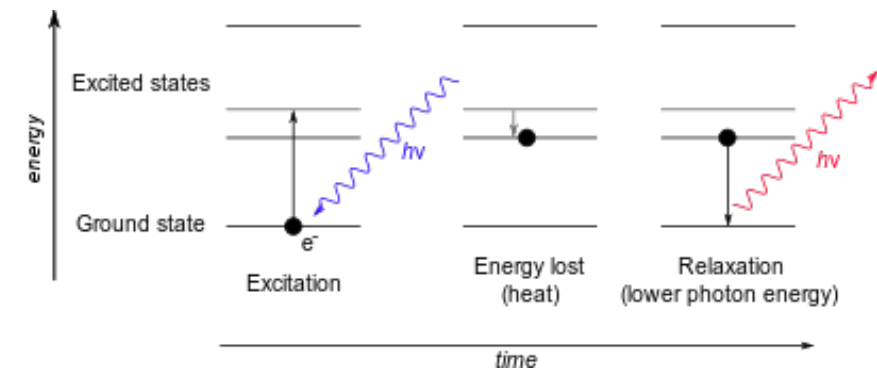


Fateme Rezaei et al 2014 J. Phys. D: Appl. Phys. 47 085401

The plasma and neutrals can also absorb radiation, either from external sources or from other regions of the plasma (re-absorption)

This is seen as a **source** of energy.

It can generate collision processes: photoexcitation, photoionization, photodissociation...



Fluorescence reaction - some photon energy is lost as heat through molecular vibrations

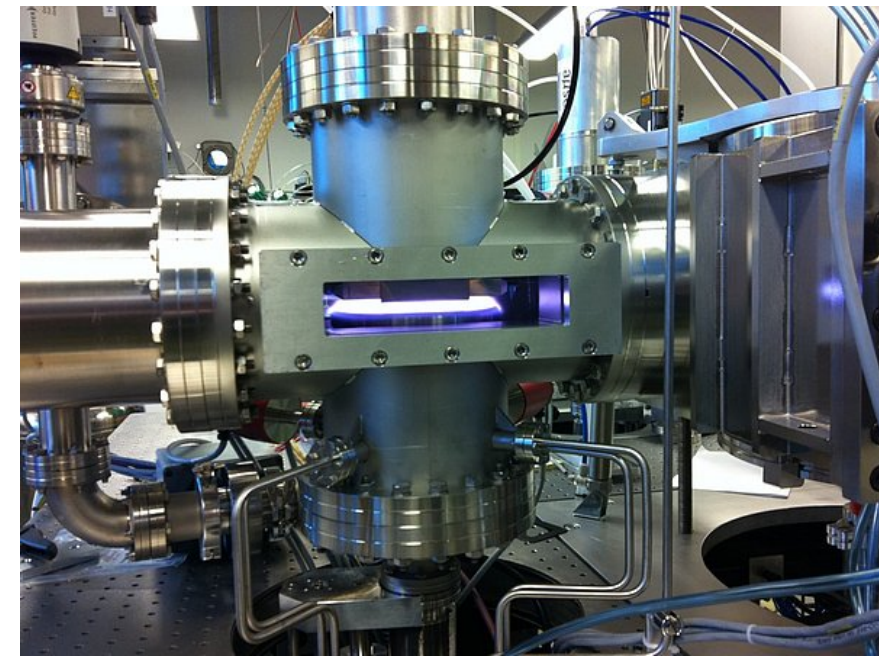
Plasma chemistry

Account for many collisional processes with accurate energy gain and losses.

Main goal is to find the distribution of excited and ionized states in a plasma.

Common too in laboratory plasmas: Plasma Reactor

Useful in models for the ionosphere.



Plasma Enhanced Chemical Vapor Deposition (PECVD) reactor at the Technical University of Eindhoven

Published in final edited form as:

Space Sci Rev. 2017 October ; 212(1-2): 731–742. doi:10.1007/s11214-017-0415-z.

SAMI3 ICON: MODEL OF THE IONOSPHERE/PLASMASPHERE SYSTEM

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The Sheffield University plasmasphere ionosphere model—a review

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(Received 18 September 1995; accepted 9 September 1996)

Cold plasma model

The kinetic pressure $\mathbf{P}_\alpha = p_\alpha \mathbf{1} + \mathbf{\Pi}_\alpha$ is neglected, therefore thermal motion of particles are neglected. Equivalently, null kinetic temperatures T_α are considered for plasma species or $f_\alpha(\mathbf{v}, \mathbf{r}, t) = n_\alpha \delta(\mathbf{v} - \mathbf{u}_\alpha)$

$$\left\{ \begin{array}{l} \frac{\partial n_\alpha}{\partial t} + \nabla \cdot (n_\alpha \mathbf{u}_\alpha) = S_\alpha - L_\alpha \\ m_\alpha n_\alpha \left(\frac{\partial \mathbf{u}_\alpha}{\partial t} + (\mathbf{u}_\alpha \cdot \nabla) \mathbf{u}_\alpha \right) = +(\rho_{e\alpha} \mathbf{E} + \mathbf{J}_{e\alpha} \wedge \mathbf{B}) + \mathbf{R}_\alpha - m_\alpha \mathbf{u}_\alpha (S_\alpha - L_\alpha) \end{array} \right.$$

Warm plasma model

Thermal motions are accounted, and it is assumed that the kinetic pressure tensor $\mathbf{P}_\alpha = p_\alpha \mathbf{1}$ is diagonal, \mathbf{q}_α and viscous forces are also assumed as null. In the isothermal motion we have $\mathbf{q}_\alpha = \kappa_T \nabla T_\alpha \sim 0$ in **isothermal** motion and also in **isentropic** flows.

$$\frac{\partial n_\alpha}{\partial t} + \nabla \cdot (n_\alpha \mathbf{u}_\alpha) = S_\alpha - L_\alpha$$

$$m_\alpha n_\alpha \left(\frac{\partial \mathbf{u}_\alpha}{\partial t} + (\mathbf{u}_\alpha \cdot \nabla) \mathbf{u}_\alpha \right) = -\nabla p_\alpha + (\rho_{e\alpha} \mathbf{E} + \mathbf{J}_{e\alpha} \wedge \mathbf{B}) + \mathbf{R}_\alpha - m_\alpha \mathbf{u}_\alpha (S_\alpha - L_\alpha)$$

$$\frac{3}{2} \frac{Dp_\alpha}{Dt} + \frac{5}{2} p_\alpha (\nabla \cdot \mathbf{u}_\alpha) = Q_\alpha - \mathbf{R}_\alpha \cdot \mathbf{u}_\alpha + \left(\frac{m_\alpha u_\alpha^2}{2} \right) (S_\alpha - L_\alpha) + \mathbf{J}_\alpha \cdot \mathbf{E}$$

Additional assumptions allow to close the system of fluid equations:

Isothermal approximation:

$$p_\alpha = n_\alpha k_B T_\alpha \rightarrow \nabla p_\alpha = k_B T_\alpha \nabla n_\alpha$$

Adiabatic approximation:

$$p_\alpha n_\alpha^{-\gamma} = \text{const.} \rightarrow \frac{\nabla p_\alpha}{p_\alpha} = \gamma \frac{\nabla n_\alpha}{n_\alpha}$$

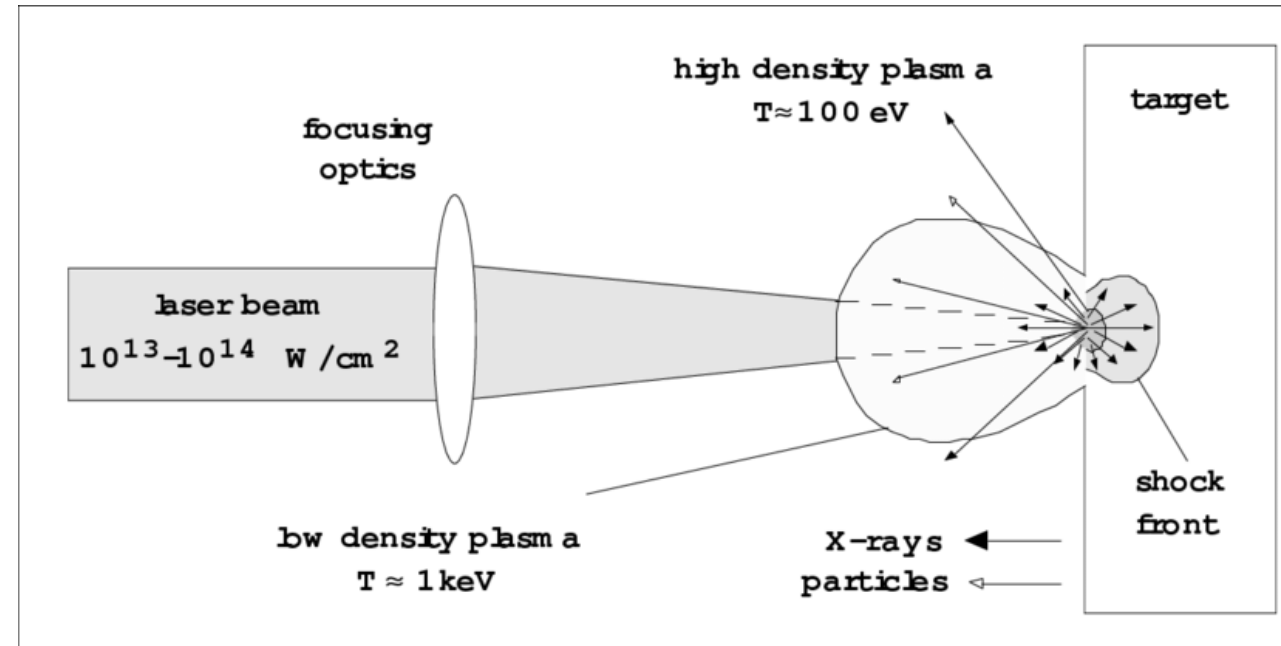
Laser-produced plasma

Basic idea: Illuminate a target material (solid or liquid) with a high-intensity laser.

The medium absorbs the energy, changing its internal energy and ionizing (out of thermodynamic equilibrium).

Generates high-density and high-temperature plasma.

Not common in the space environment (yet), but recently useful to recreate astrophysical plasmas that contribute to the space environment.



Giulietti, D., & Gizzi, L. A. (1998). X-ray emission from laser-produced plasmas. *La Rivista del Nuovo Cimento* (1978-1999), 21(10), 1-93.

High Power Laser Science and Engineering, (2021), Vol. 9, e49, 34 pages.
doi: 10.1017/hpl.2021.35



REVIEW

Recent progress of laboratory astrophysics with intense lasers

Hideaki Takabe^{1,2,3} and Yasuhiro Kuramitsu^{1,2}

Spectroscopy

We can employ the radiation from a plasma to estimate its characteristics.

Each process emits radiation in a certain wavelength, related to the energy

$$E = \frac{hc}{\lambda}$$

However, complex process as it requires detail analysis dealing with optic systems, quantum effects, Doppler effect, required knowledge of transition processes, cross sections...

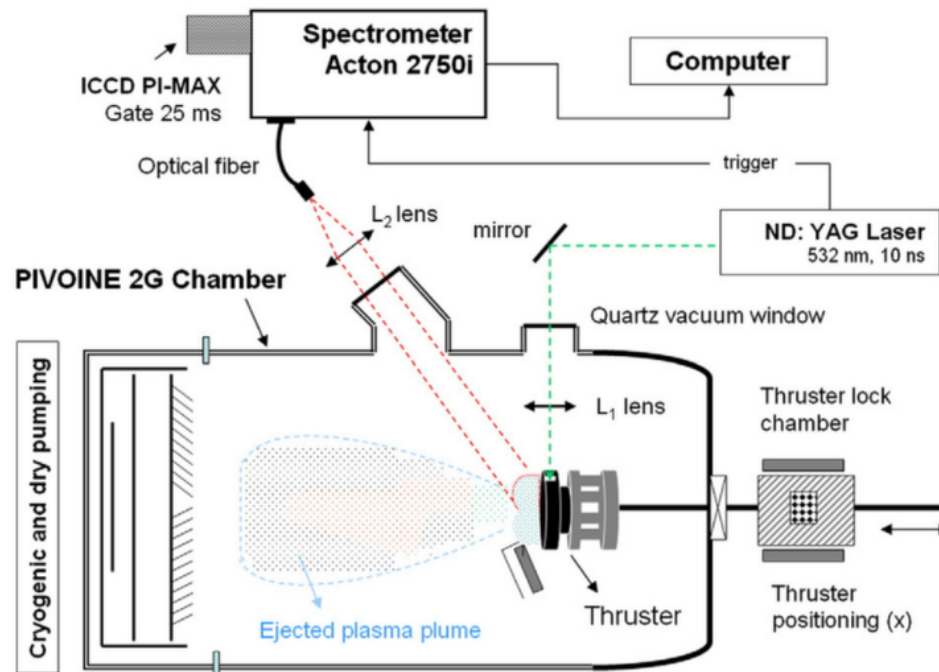


Fig. 1. Experimental set-up.

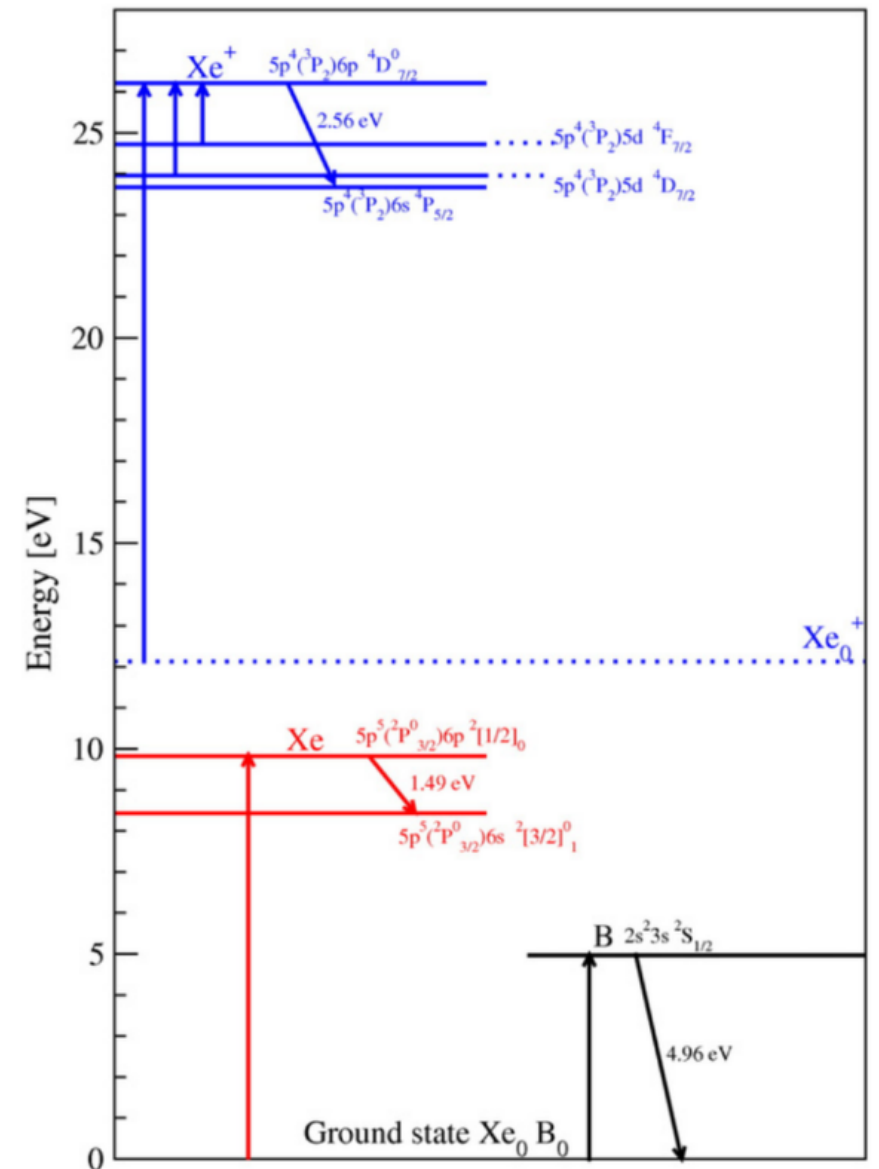


Fig. 2. Simplified energy diagram of Bi, XeI and XeII (only the levels of interest for this study are represented).

Balika, L., Focsa, C., Gurlui, S., Pellerin, S., Pellerin, N., Pagnon, D., & Dudeck, M. (2012). Laser-induced breakdown spectroscopy in a running Hall Effect Thruster for space propulsion. *Spectrochimica Acta Part B: Atomic Spectroscopy*, 74, 184-189.