Multi-Physics Magnetohydrodynamics and Radiation Gas Dynamic Numerical Simulation Models for Aerospace Applications

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Outline

1. General Definitions of Radiative Gas Dynamics (RadGD)
2. Simplification of RadGD governing equations
3. Examples of the RadGD problems
4. Radiation Heat Transfer theory
5. Spectral optical properties of gases and plasmas
6. RadGD for aerospace applications: Numerical simulation results
7. Modern challenging problems of RGD
8. On-going efforts

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RadGD/MHD: Interaction modes

- Quantum and relativistic interaction
- Strong RGD interaction
- Weak RGD interaction
- No RGD interaction/Quantum description of elementary radiative processes
- No RGD interaction/Phenomenology of radiative processes

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RadGD/MHD: Governing equations

$$\frac{\partial \rho}{\partial t} + div\, \rho \mathbf{V} = \dot{\varpi}_{Rad}$$

$$p = \frac{R_0}{M} \rho T$$

$$\frac{\partial \rho \mathbf{V}}{\partial t} + div\left[(\rho \mathbf{V}) \cdot \mathbf{V}\right] = -grad\left(p + p^{Rad}\right) - \frac{1}{\mu_0}\left[\mathbf{J} \times \mathbf{B}\right] + \mathbf{F}_\tau + \mathbf{F}_\tau^{Rad} + \mathbf{g}\rho + \rho_e \mathbf{E}$$

$$\frac{\partial}{\partial t}\left(\rho e + \frac{\rho \mathbf{V}^2}{2} + \frac{\mathbf{B}^2}{2\mu_0} + U_{Rad}\right) + div\left[\rho \mathbf{V}\left(e + \frac{\mathbf{V}^2}{2} + \frac{p}{\rho} + \frac{p_m}{\rho} + \frac{p^{Rad}}{\rho}\right)\right] =$$

$$= div\left(\lambda grad T\right) + div \mathbf{W}_{Rad} + A_\tau + A_\tau^{Rad} + \rho\left(\mathbf{g} \cdot \mathbf{V}\right) + \left(\mathbf{J} \cdot \mathbf{E}\right)$$

$$rot\, \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad div\, \mathbf{D} = \rho_e \qquad div\, \mathbf{B} = 0 \qquad \frac{1}{\mu_0} rot\, \mathbf{B} = \mathbf{J}$$

$$\mathbf{J} + P_H\left[\mathbf{J} \times \mathbf{B}\right] = \sigma_e\left(\mathbf{E} + \left[\mathbf{V} \times \mathbf{B}\right] + \frac{1}{en_e} grad\, p_e\right)$$

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The **Boltzmann** equation for the photon gas: the Radiation Heat Transfer equation

$$\frac{1}{c}\frac{\partial J_\nu(s,\mathbf{\Omega},t)}{\partial t}+\frac{\partial J_\nu(s,\mathbf{\Omega},t)}{\partial s}+\left[\kappa_\nu(s)+\sigma_\nu(s)\right]J_\nu(s,\mathbf{\Omega},t)=$$

$$=J_\nu^{em}(s,t)+\frac{1}{4\pi}\sigma_\nu(s)\int_{\nu'=0}^{\infty}\int_{\Omega'=4\pi}\boxed{p(s;\mathbf{\Omega}',\mathbf{\Omega};\nu',\nu)}J_{\nu'}(s,\mathbf{\Omega}',t)\,d\Omega'\,d\nu'$$

$\kappa_\nu(s)$ is the spectral absorption coefficient

$\sigma_\nu(s)$ is the spectral scattering coefficient

$\boxed{p(s;\mathbf{\Omega}',\mathbf{\Omega};\nu',\nu)}$ is the phase function for scattering

The general characteristics of the radiation heat transfer theory:

$\boxed{J_\nu(s,\mathbf{\Omega},t)}$ is the spectral intensity of a radiation field

$\boxed{J_\nu^{em}(s,t)}$ is the spectral intensity of a medium emissivity

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General characteristics of the Radiation Heat Transfer (RHT) theory

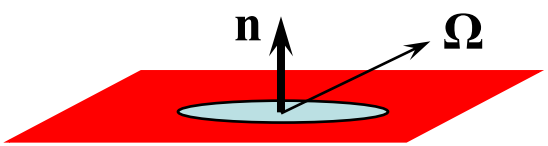
$$U_\nu = \frac{1}{c}\int_{4\pi} J_\nu(s,\mathbf{\Omega})\,\mathrm{d}\Omega$$ **is the spectral energy density**

$$\mathbf{W}_\nu = \int_{4\pi} J_\nu(s,\mathbf{\Omega})\mathbf{\Omega}\,\mathrm{d}\Omega$$ **is the spectral radiation flux**

$$Q_{\nu,Rad} = div\mathbf{W}_\nu$$ **is the spectral radiation flux divergence**

This is the heat source due to RHT

$$\mathbf{q}_{\nu,Rad,\mathbf{n}} = (\mathbf{W}_\nu\cdot\mathbf{n}) = \int_{4\pi} J_\nu(s,\mathbf{\Omega})(\mathbf{\Omega}\cdot\mathbf{n})\,\mathrm{d}\Omega$$ **is the spectral hemispherical flux**



Corresponding integral (total) characteristics:

$$U_{Rad} = \int_0^\infty U_\nu\,\mathrm{d}\omega$$

$$\mathbf{W}_{Rad} = \int_0^\infty \mathbf{W}_\nu\,\mathrm{d}\nu$$

$$\mathbf{q}_{Rad,\mathbf{n}} = \int_0^\infty \mathbf{q}_{Rad,\nu,\mathbf{n}}\,\mathrm{d}\nu$$

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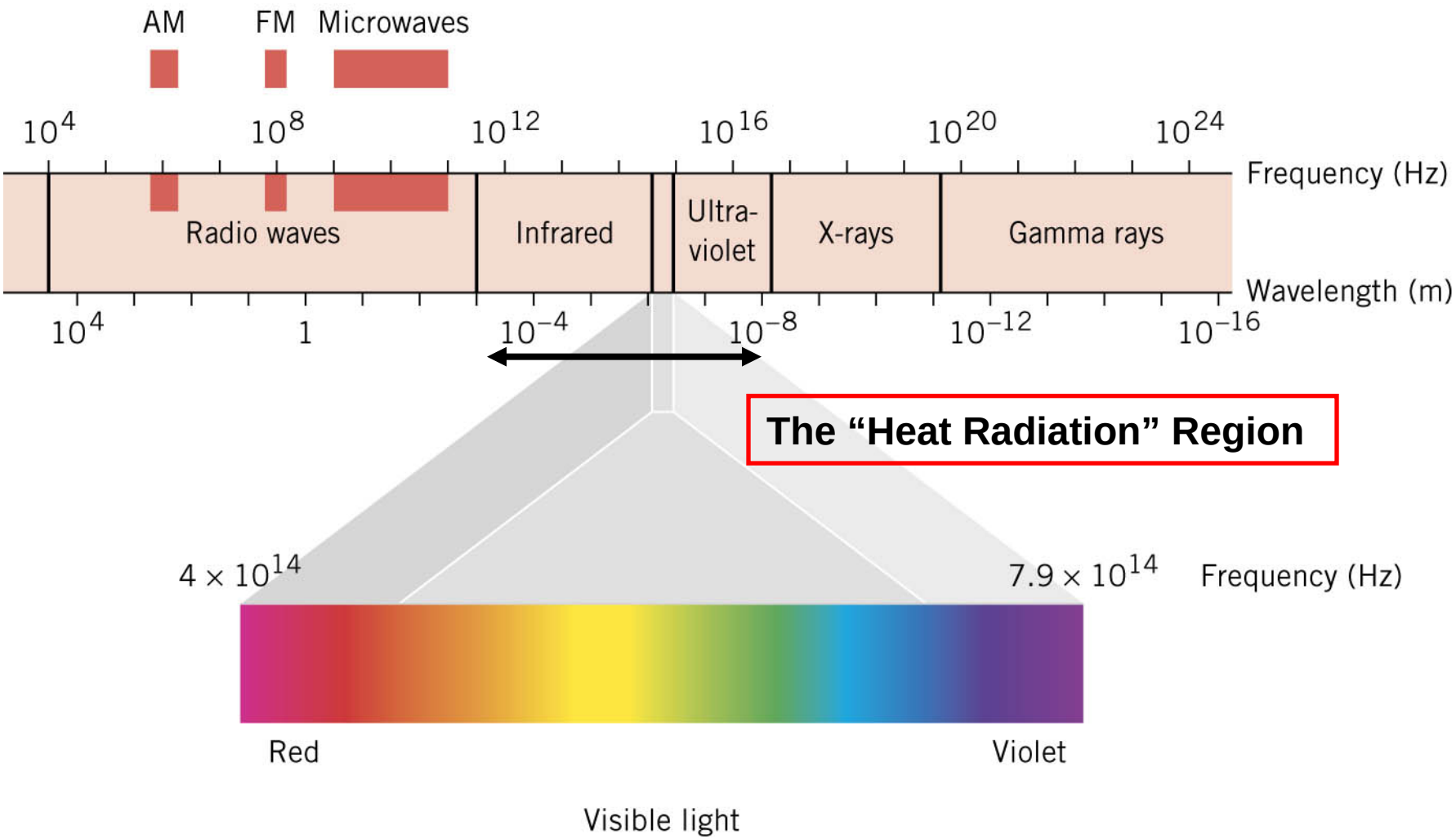
Scale of the Electromagnetic Waves



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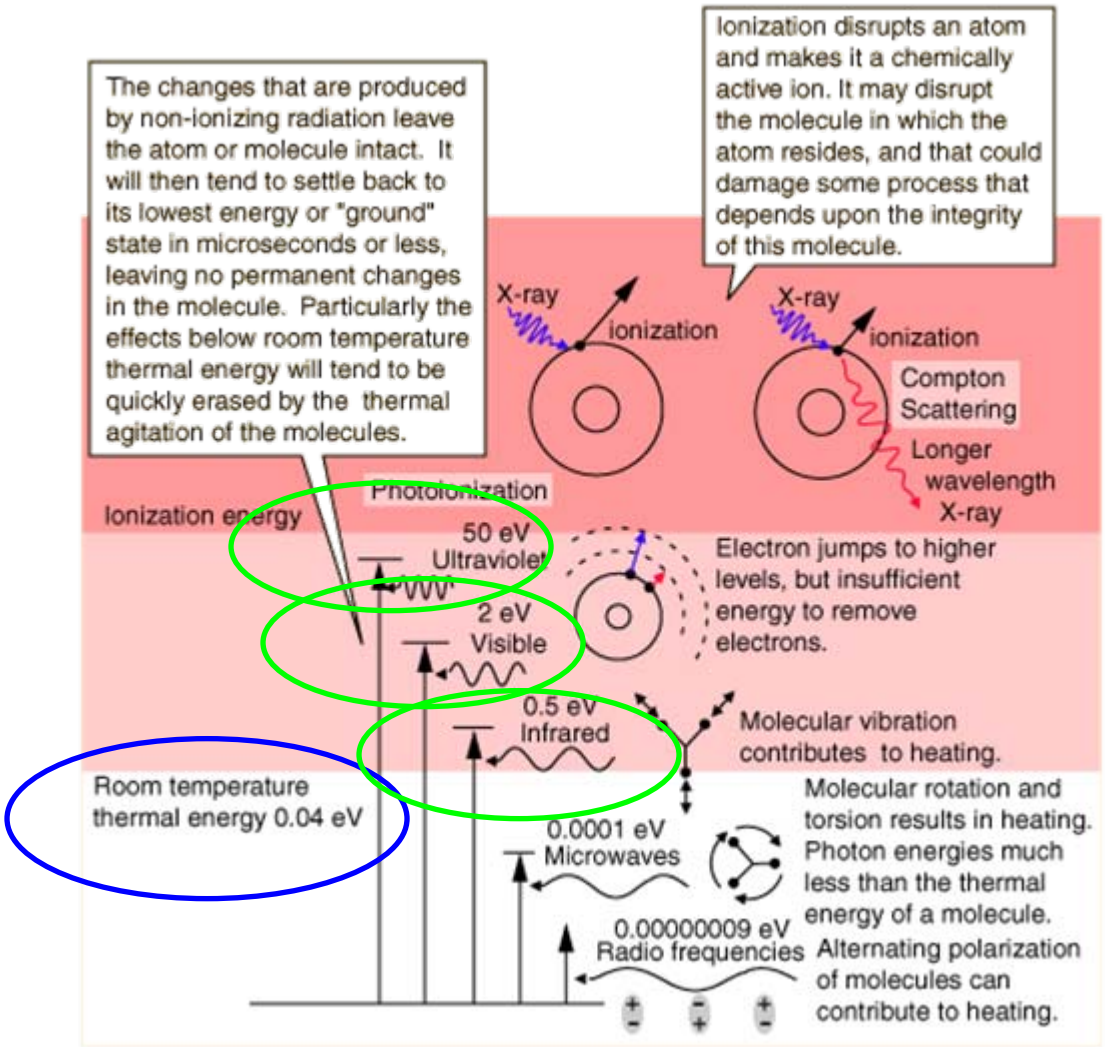
Energy scales of radiation/medium interaction.

Significant physical fact is:
wavelength of the "heat radiation" is compatible with typical size of atomic and molecular particles



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Simplification of the MHD/RadGD governing equations

$$\frac{\partial \rho}{\partial t} + div\, \rho \mathbf{V} = \dot{\varpi}_{Rad}$$

$$p = \frac{R_0}{M} \rho T$$

$$\frac{\partial \rho \mathbf{V}}{\partial t} + div\left[\left(\rho \mathbf{V}\right) \cdot \mathbf{V}\right] = -grad\left(p + p^{Rad}\right) - \cancel{\frac{1}{\mu_0}\left[\mathbf{J} \times \mathbf{B}\right]} + \mathbf{F}_\tau + \mathbf{F}_\tau^{Rad} + \mathbf{g}\rho + \cancel{\rho_e \mathbf{E}}$$

$$\frac{\partial}{\partial t}\left(\rho e + \frac{\rho \mathbf{V}^2}{2} + \cancel{\frac{\mathbf{B}^2}{2\mu_0}} + U_{Rad}\right) + div\left[\rho \mathbf{V}\left(e + \frac{\mathbf{V}^2}{2} + \frac{p}{\rho} + \cancel{\frac{p_m}{\rho}} + \frac{p^{Rad}}{\rho}\right)\right] =$$

$$= div\left(\lambda grad T\right) + div \mathbf{W}_{Rad} + A_\tau + A_\tau^{Rad} + \rho\left(\mathbf{g} \cdot \mathbf{V}\right) + \cancel{\left(\mathbf{J} \cdot \mathbf{E}\right)}$$

$$\frac{1}{c}\frac{\partial J_\nu\left(s, \mathbf{\Omega}, t\right)}{\partial t} + \frac{\partial J_\nu\left(s, \mathbf{\Omega}, t\right)}{\partial s} + \left[\kappa_\nu\left(s\right) + \sigma_\nu\left(s\right)\right] J_\nu\left(s, \mathbf{\Omega}, t\right) =$$

$$= J_\nu^{em}\left(s, t\right) + \frac{1}{4\pi}\sigma_\nu\left(s\right) \int_{\nu'=0}^{\infty} \int_{\Omega'=4\pi} p\left(s; \mathbf{\Omega}', \mathbf{\Omega}; \nu', \nu\right) J_{\nu'}\left(s, \mathbf{\Omega}', t\right) d\Omega' d\nu'$$

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RadGD: Governing equations

$$\frac{\partial \rho}{\partial t} + div\, \rho \mathbf{V} = \dot{\varpi}_{Rad}$$

$$p = \frac{R_0}{M} \rho T$$

$$\frac{\partial \rho \mathbf{V}}{\partial t} + div\left[(\rho \mathbf{V}) \cdot \mathbf{V} \right] = -grad\left(p + p^{Rad} \right) + \mathbf{F}_\tau + \mathbf{F}_\tau^{Rad} + \mathbf{g}\rho$$

$$\frac{\partial}{\partial t}\left(\rho e + \frac{\rho \mathbf{V}^2}{2} + U_{Rad} \right) + div\left[\rho \mathbf{V} \left(e + \frac{\mathbf{V}^2}{2} + \frac{p}{\rho} + \frac{p^{Rad}}{\rho} \right) \right] =$$

$$= div\left(\lambda grad T \right) + div \mathbf{W}_{Rad} + A_\tau + A_\tau^{Rad} + \rho\left(\mathbf{g} \cdot \mathbf{V} \right)$$

?

$$\frac{1}{c}\frac{\partial J_\nu(s,\mathbf{\Omega},t)}{\partial t} + \frac{\partial J_\nu(s,\mathbf{\Omega},t)}{\partial s} + \left[\kappa_\nu(s) + \sigma_\nu(s) \right] J_\nu(s,\mathbf{\Omega},t) =$$

$$= J_\nu^{em}(s,t) + \frac{1}{4\pi}\sigma_\nu(s) \int_{\nu'=0}^{\infty} \int_{\Omega'=4\pi} p(s;\mathbf{\Omega}',\mathbf{\Omega};\nu',\nu) J_{\nu'}(s,\mathbf{\Omega}',t)\, d\Omega'\, d\nu'$$

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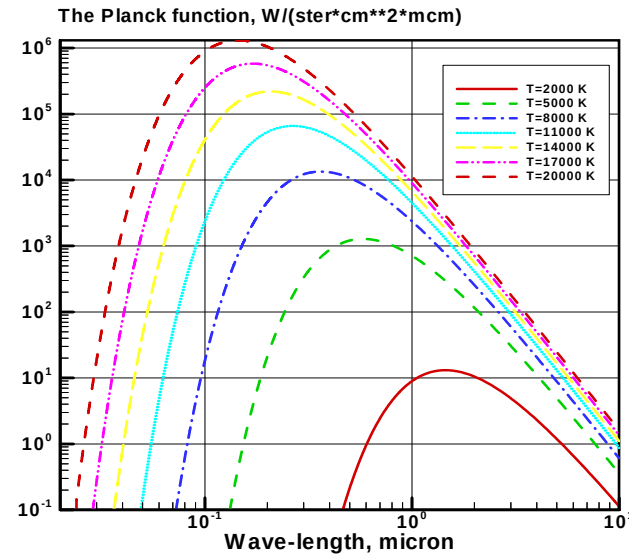
General Physics: Simplest estimations

Radiative energy

$$\frac{\partial}{\partial t}\left(\rho e+\frac{\rho \mathbf{V}^2}{2}+\cancel{U_{Rad}}\right)+div\left[\rho\mathbf{V}\left(e+\frac{\mathbf{V}^2}{2}+\frac{p}{\rho}+\frac{p^{Rad}}{\rho}\right)\right]=$$

$$=div\left(\lambda gradT\right)+div\mathbf{W}_{Rad}+A_\tau+A_\tau^R+\rho\left(\mathbf{g}\cdot\mathbf{V}\right)$$



$$U_{Rad}=\frac{\tilde{\sigma}}{c}T^4$$

$$\tilde{\sigma}=5.67\cdot10^{-5}\ \frac{erg}{cm^2\cdot s\cdot K^4}$$

T, K	U_{Rad}, erg/cm^3	U_{Int}, erg/cm^3
10 000	$\sim 2\cdot10^1$	$\sim 10^6$
100 000	$\sim 2\cdot10^5$	$\sim 10^{12}$

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General Physics: Simplest estimations

Radiative pressure

$$\frac{\partial \rho \mathbf{V}}{\partial t} + div\left[\left(\rho \mathbf{V}\right)\cdot \mathbf{V}\right] = -grad\left(p + p^R\right) + \mathbf{F}_\tau + \mathbf{F}_\tau^R + \mathbf{g}\rho$$

$$p^R = \frac{1}{3}U_{Rad} = \frac{1}{3}\frac{\tilde{\sigma}}{c}T^4$$

$$\tilde{\sigma} = 5.67\cdot 10^{-5}\ \frac{erg}{cm^2\cdot s\cdot K^4}$$

T, K	p^R, erg/cm^3
1000	$\sim 10^{-3}$
10 000	$\sim 10^{1}$
100 000	$\sim 10^{5}$

The normal conditions: p=10^6 erg/cm^3

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General Physics: Simplest estimations

Gas/Plasma heating

$$\frac{\partial}{\partial t}\left(\rho e+\frac{\rho \mathbf{V}^2}{2}\right)+div\left[\rho\mathbf{V}\left(e+\frac{\mathbf{V}^2}{2}+\frac{p}{\rho}\right)\right]=$$

$$=div\left(\lambda gradT\right)+div\mathbf{W}_{Rad}+A_\tau\rho\left(\mathbf{g}\cdot\mathbf{V}\right)$$

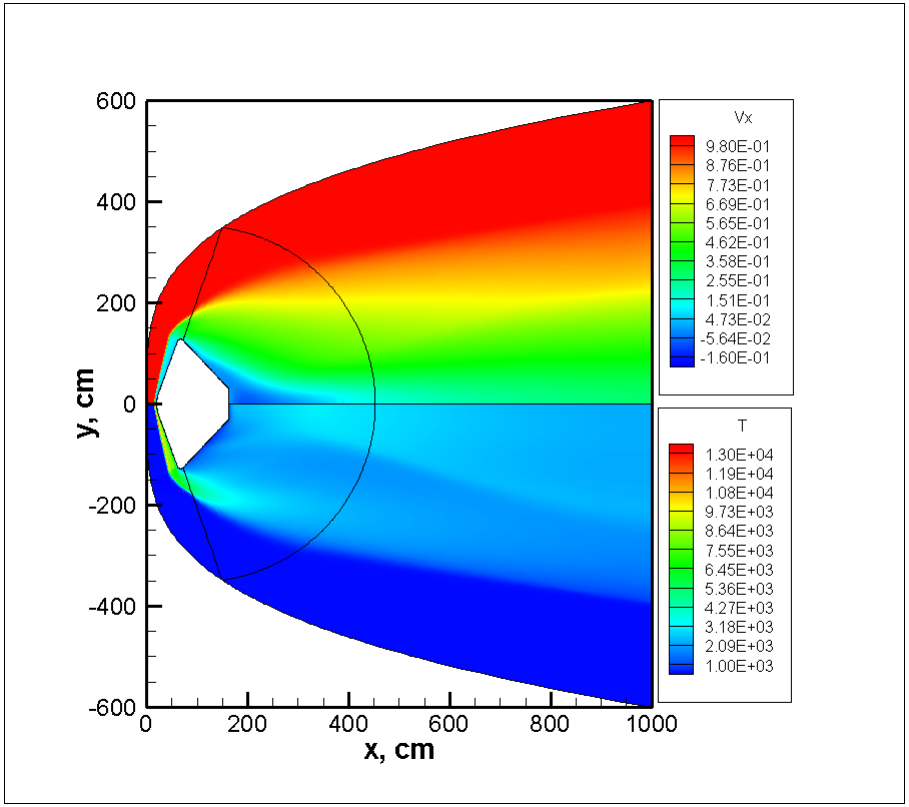
$$V_\infty \sim 10^{+5}\ \ cm/s$$!!!

$$\rho_\infty \sim 10^{-6}\ \ erg/cm^3$$

$$\rho_\infty V_\infty^3 \sim 10^{+9}\ \left[\frac{erg\cdot cm}{cm^3\cdot s}=\frac{erg}{cm\cdot s}\right]$$

$$W_R \sim \tilde{\sigma}T^4$$

T=10^4 K: $$W_R=5.67\cdot 10^{11}\ \frac{erg}{s\cdot cm^2}$$



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RadGD: Last simplifications

$$\frac{\partial \rho}{\partial t} + div\, \rho \mathbf{V} = \cancel{\dot{\varpi}_{Rad}}$$

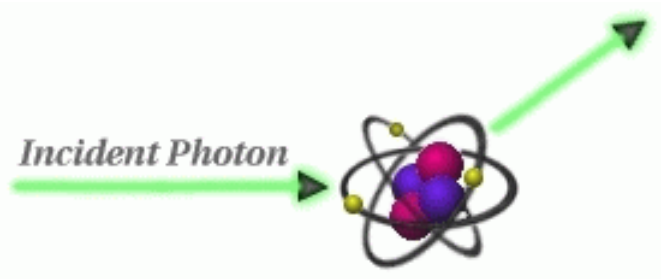
$$\cancel{\frac{1}{c}\frac{\partial J_\nu(s,\mathbf{\Omega},t)}{\partial t}} + \frac{\partial J_\nu(s,\mathbf{\Omega},t)}{\partial s} + \left[\kappa_\nu(s) + \sigma_\nu(s)\right] J_\nu(s,\mathbf{\Omega},t) =$$

$$= J_\nu^{em}(s,t) + \frac{1}{4\pi}\sigma_\nu(s)\int_{\nu'=0}^{\infty}\int_{\Omega'=4\pi} p(s;\mathbf{\Omega}',\mathbf{\Omega};\nu',\nu) J_{\nu'}(s,\mathbf{\Omega}',t)\, d\Omega'\, d\nu'$$

$$c = 3\cdot 10^{10}\ cm/s >> V_\infty \sim 10^5\ cm/s$$

$$p^R << p$$

Assumption of the coherent scattering:



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RadGD: Governing equations

$$\frac{\partial \rho}{\partial t} + div\, \rho \mathbf{V} = 0$$

$$p = \frac{R_0}{M} \rho T$$

$$\frac{\partial \rho \mathbf{V}}{\partial t} + div\left[\left(\rho \mathbf{V}\right) \cdot \mathbf{V}\right] = -grad\left(p\right) + \mathbf{F}_\tau + \mathbf{g}\rho$$

$$\frac{\partial}{\partial t}\left(\rho e + \frac{\rho \mathbf{V}^2}{2}\right) + div\left[\rho \mathbf{V}\left(e + \frac{\mathbf{V}^2}{2} + \frac{p}{\rho}\right)\right] =$$
$$= div\left(\lambda grad T\right) + div \mathbf{W}_{Rad} + A_\tau + \rho\left(\mathbf{g} \cdot \mathbf{V}\right)$$

$$\frac{\partial J_\nu\left(s, \mathbf{\Omega}, t\right)}{\partial s} + \left[\kappa_\nu\left(s\right) + \sigma_\nu\left(s\right)\right] J_\nu\left(s, \mathbf{\Omega}, t\right) =$$
$$= J_\nu^{em}\left(s, t\right) + \frac{1}{4\pi}\sigma_\nu\left(s\right) \int\limits_{\Omega' = 4\pi} p\left(s; \mathbf{\Omega}', \mathbf{\Omega}; \nu\right) J_{\nu'}\left(s, \mathbf{\Omega}', t\right) d\Omega'$$

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MHD/RadGD: Governing equations

$$\frac{\partial \rho}{\partial t} + div\, \rho \mathbf{V} = 0$$

$$p = \frac{R_0}{M} \rho T$$

$$\frac{\partial \rho \mathbf{V}}{\partial t} + div\left[(\rho \mathbf{V}) \cdot \mathbf{V}\right] = -grad(p) - \frac{1}{\mu_0}\left[\mathbf{J} \times \mathbf{B}\right] + \mathbf{F}_\tau + \mathbf{g}\rho + \rho_e \mathbf{E}$$

$$\frac{\partial}{\partial t}\left(\rho e + \frac{\rho \mathbf{V}^2}{2} + \frac{\mathbf{B}^2}{2\mu_0}\right) + div\left[\rho \mathbf{V}\left(e + \frac{\mathbf{V}^2}{2} + \frac{p}{\rho} + \frac{p_m}{\rho}\right)\right] =$$
$$= div\left(\lambda grad T\right) + div \mathbf{W}_{Rad} + A_\tau + \rho\left(\mathbf{g} \cdot \mathbf{V}\right) + \left(\mathbf{J} \cdot \mathbf{E}\right)$$

$$\frac{\partial J_\nu(s, \mathbf{\Omega}, t)}{\partial s} + \left[\kappa_\nu(s) + \sigma_\nu(s)\right] J_\nu(s, \mathbf{\Omega}, t) =$$
$$= J_\nu^{em}(s,t) + \frac{1}{4\pi}\sigma_\nu(s) \int_{\Omega'=4\pi} p(s; \mathbf{\Omega}', \mathbf{\Omega}; \nu) J_{\nu'}(s, \mathbf{\Omega}', t)\, d\Omega'$$

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Examples of RadGD problems

- Outer Space
- World of the Sun and Planets
- Planetary atmospheres
- Natural phenomena
- Physical phenomena
- Aerospace applications

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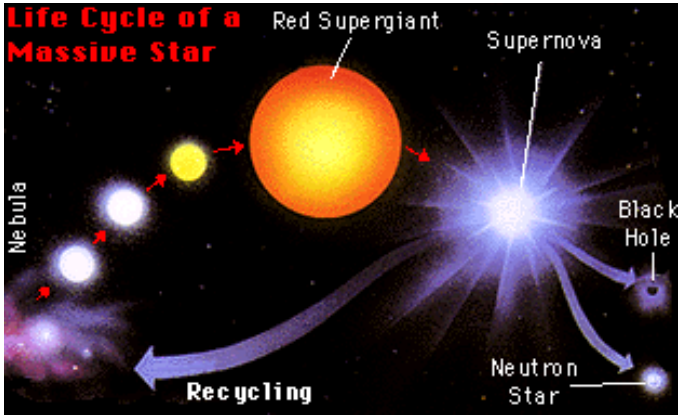
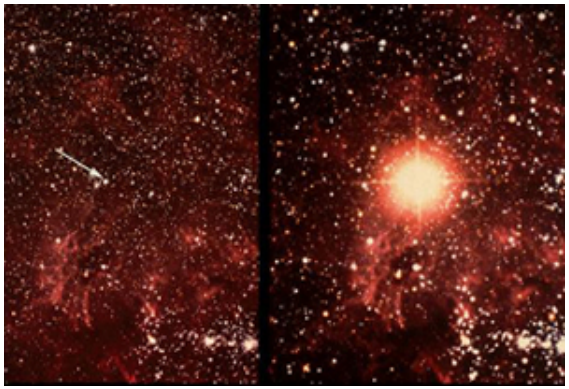
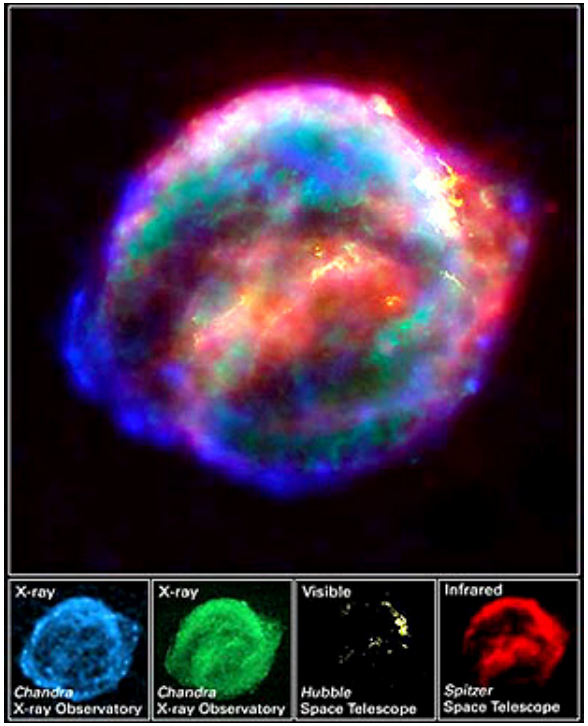
Examples of RadGD problems





Outer Space:

- Quantum and relativistic interaction
- Strong RadGD interaction
- Huge energies
- Strong RadGD interaction
- Relativistic radiative gas dynamics



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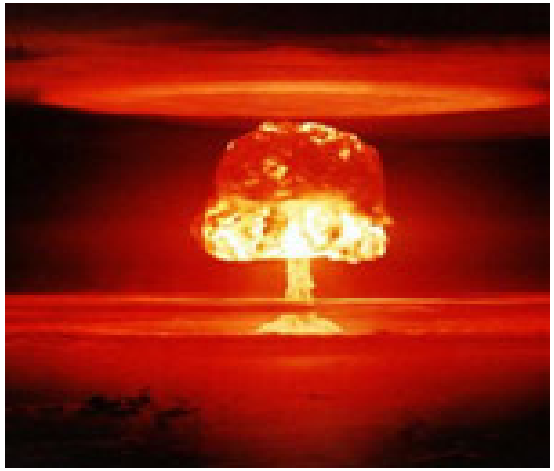
Examples of RadGD problems

Physical phenomena : Nuclear explosions

- Strong RGD interaction
- Huge energy



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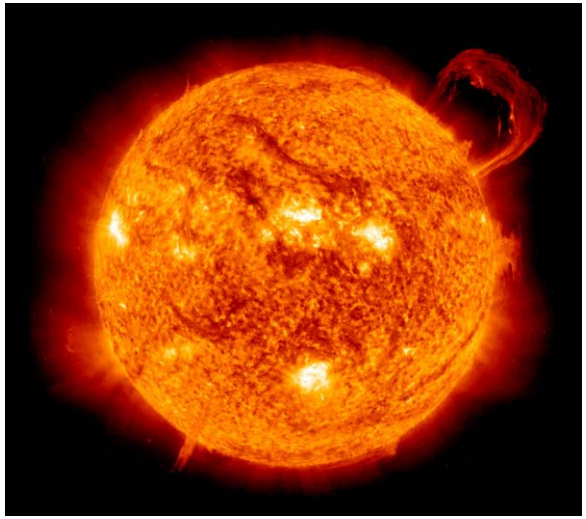
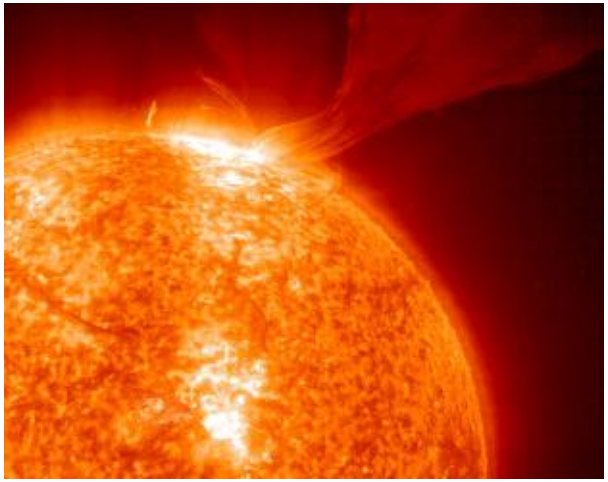
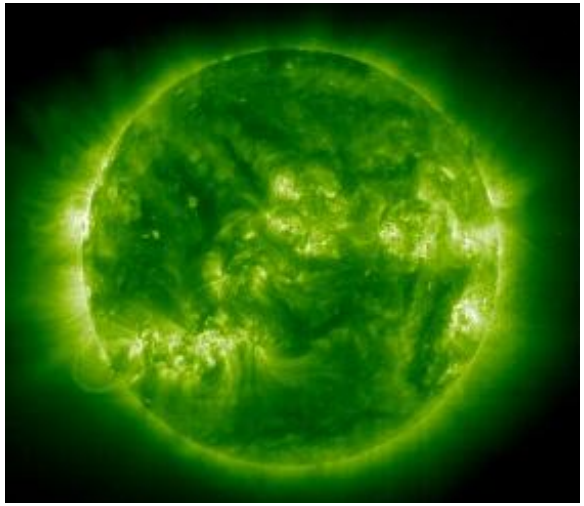
Examples of RadGD problems

World of the Sun and Planets :

- Huge energies
- Strong RGD interaction
- Strong MHD/RGD interaction







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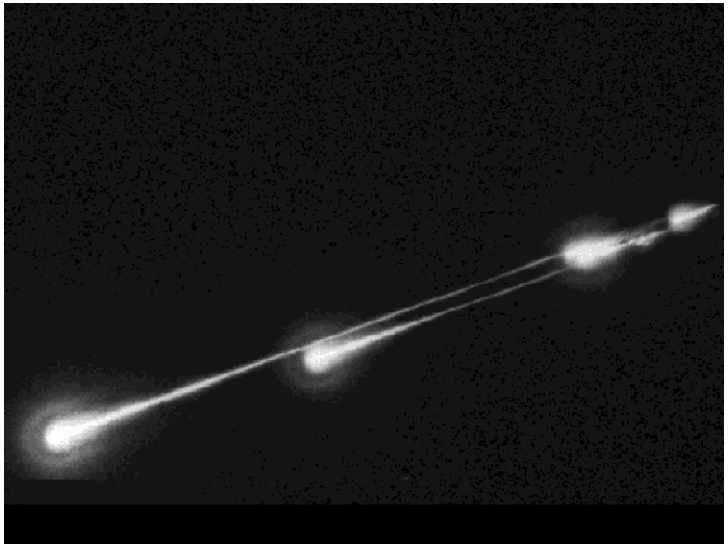
Examples of RadGD problems

Physics of comets and asteroids :

- Strong RGD interaction
- Hypersonic flows



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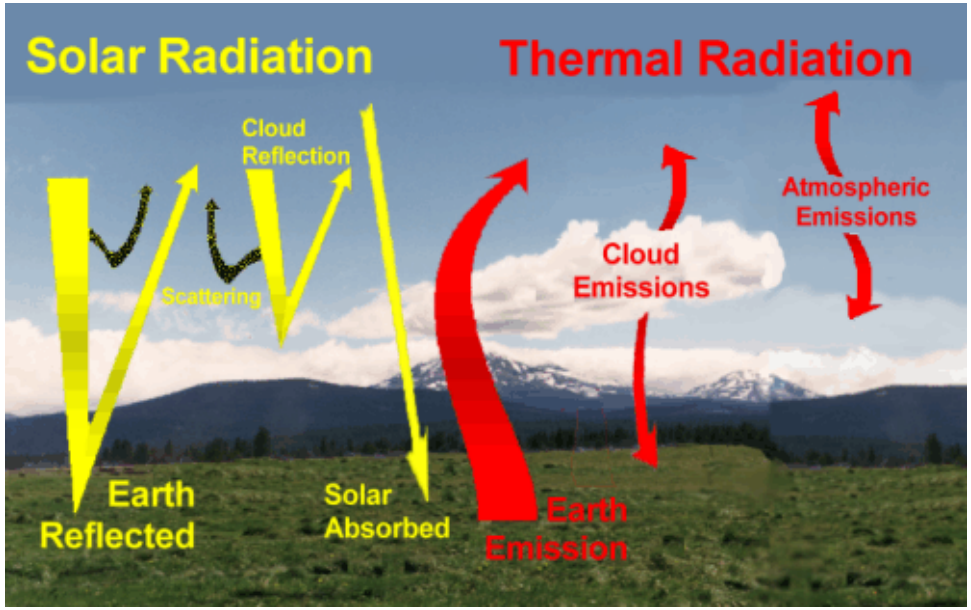
Examples of RadGD problems

Planetary atmospheres :

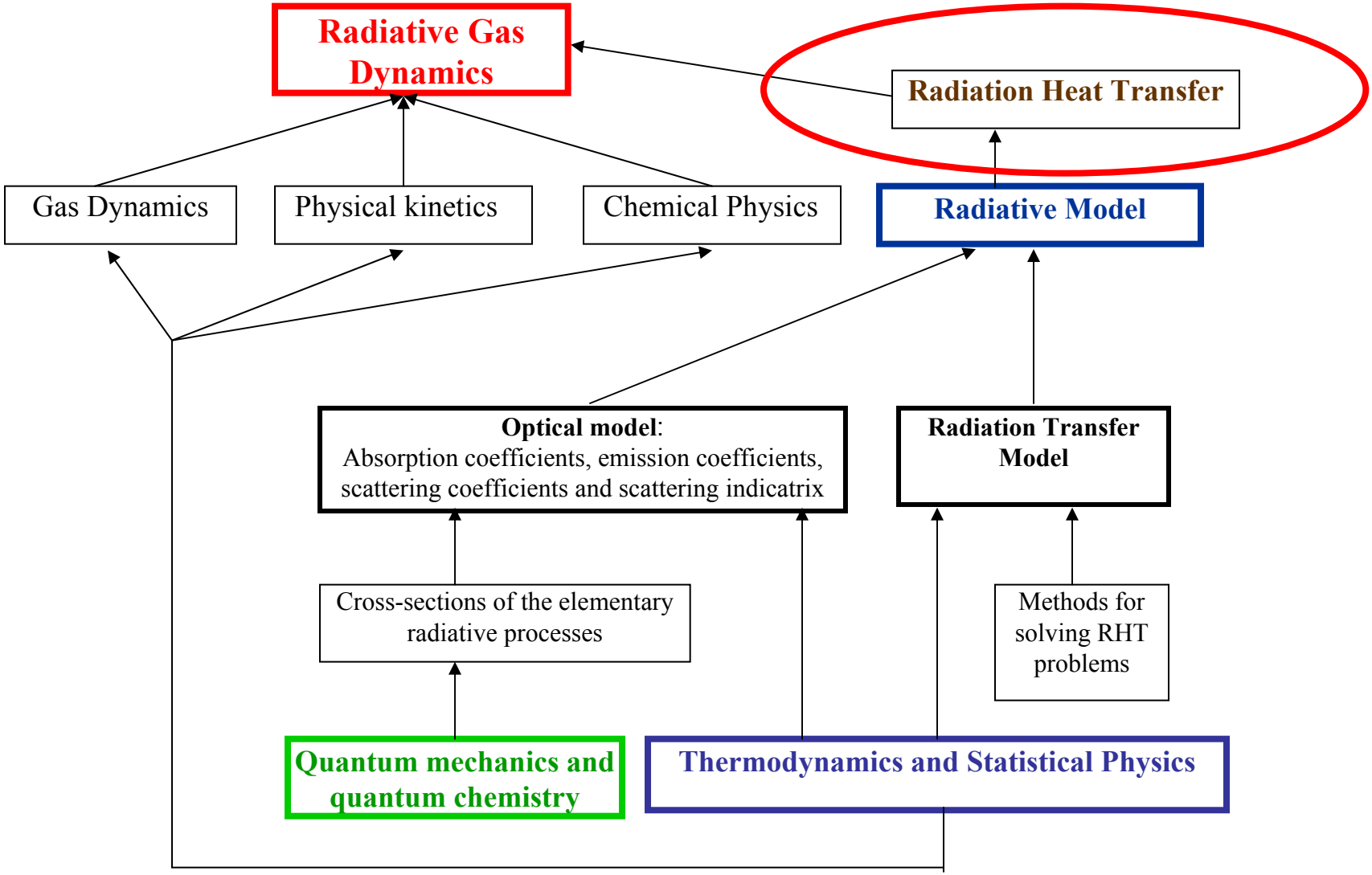
- Strong RGD interaction (!!!)
- Essentially subsonic gasdynamics



Theoretical basis and general definitions:

Radiation Heat Transfer equation

Multi-Physics MHD/RadGD Numerical Simulation Models



The Radiation Heat Transfer (RHT) equation:

$$\frac{\partial J_\omega\left(s,\vec{\Omega}\right)}{\partial s}+\kappa_\omega J_\omega\left(s,\vec{\Omega}\right)+\sigma_\omega J_\omega\left(s,\vec{\Omega}\right)=j_\omega\left(s\right)+\frac{\sigma_\omega}{4\pi}\int_{4\pi} p_\omega\left(s,\vec{\Omega}'\to\vec{\Omega}\right)\cdot J_\omega\left(\vec{\Omega}'\right)\mathrm{d}\vec{\Omega}'$$

$J_\omega\left(s,\vec{\Omega}\right)$ is the spectral intensity

$\kappa_\omega\left(s\right)$ is the spectral absorption coefficient

$\sigma_\omega\left(s\right)$ is the spectral scattering coefficient

$p_\omega\left(s,\vec{\Omega}'\to\vec{\Omega}\right)$ is the phase function for scattering

Two significant simplifications of the RHT equation:

1) The Local Thermodynamic Equilibrium (LTE)

$$j_\omega(s)=\kappa_\omega J_{b,\omega}\left[T\left(s\right)\right]$$

where $J_{b,\omega}\left[T\left(s\right)\right]$ is the **Planck intensity**

2) Non-scattering medium $\sigma_\omega\left(s\right)=0$

LTE: Radiative energy balance

$$\left(\vec{\nabla}\cdot\vec{W}\right)=4\pi\int_0^\infty \kappa_\omega J_{b,\omega}\,\mathrm{d}\omega - c\int_0^\infty \kappa_\omega U_\omega\,\mathrm{d}\omega$$

is the integral (total) heat source in the energy conservation equation due to radiative processes

$$\kappa_P=\frac{\int \kappa_\omega J_{b,\omega}\,\mathrm{d}\omega}{\int J_{b,\omega}\,\mathrm{d}\omega}$$

is the **Planck-mean absorption coefficient**

$$\int J_{b,\omega}\,\mathrm{d}\omega=\frac{\tilde{\sigma}}{\pi}T^4\,,\quad \tilde{\sigma}=5.67\times10^{-12}\,\frac{\mathrm{W}}{\mathrm{cm}^2\mathrm{K}^4}$$

is the **Stefan-Boltzmann constant**

$$\left(\vec{\nabla}\cdot\vec{W}\right)=4\kappa_P\tilde{\sigma}T^4-c\int_0^\infty \kappa_\omega U_\omega\,\mathrm{d}\omega \qquad \frac{\mathrm{Watt}}{\mathrm{cm}^3}$$

integral emission

integral absorption

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Basis of the RHT theory: Summary

1. The spectral and integral emissivities are described by the following formulas (**only for the LTE approximation** !)

$$Q_{em,\lambda} = 4\pi\kappa_\lambda \; J_{b,\lambda} \; , \quad \frac{\text{Watt}}{\text{cm}^3 \cdot \mu}$$

$$Q_{em} = 4\kappa_P \; \tilde{\sigma} T^4 , \quad \frac{\text{Watt}}{\text{cm}^3}$$

2. The spectral and integral emissivity are determined by the spectral absorption coefficient, which is determined in one's turn as the following function:

$$\kappa_\nu = \kappa\left(\begin{Bmatrix} \nu \\ \lambda \\ \omega \end{Bmatrix}, T, p\right) \quad \text{or} \quad \kappa_\nu = \kappa\left(\begin{Bmatrix} \nu \\ \lambda \\ \omega \end{Bmatrix}, T, p_\Sigma, x_1, \ldots, x_N\right)$$

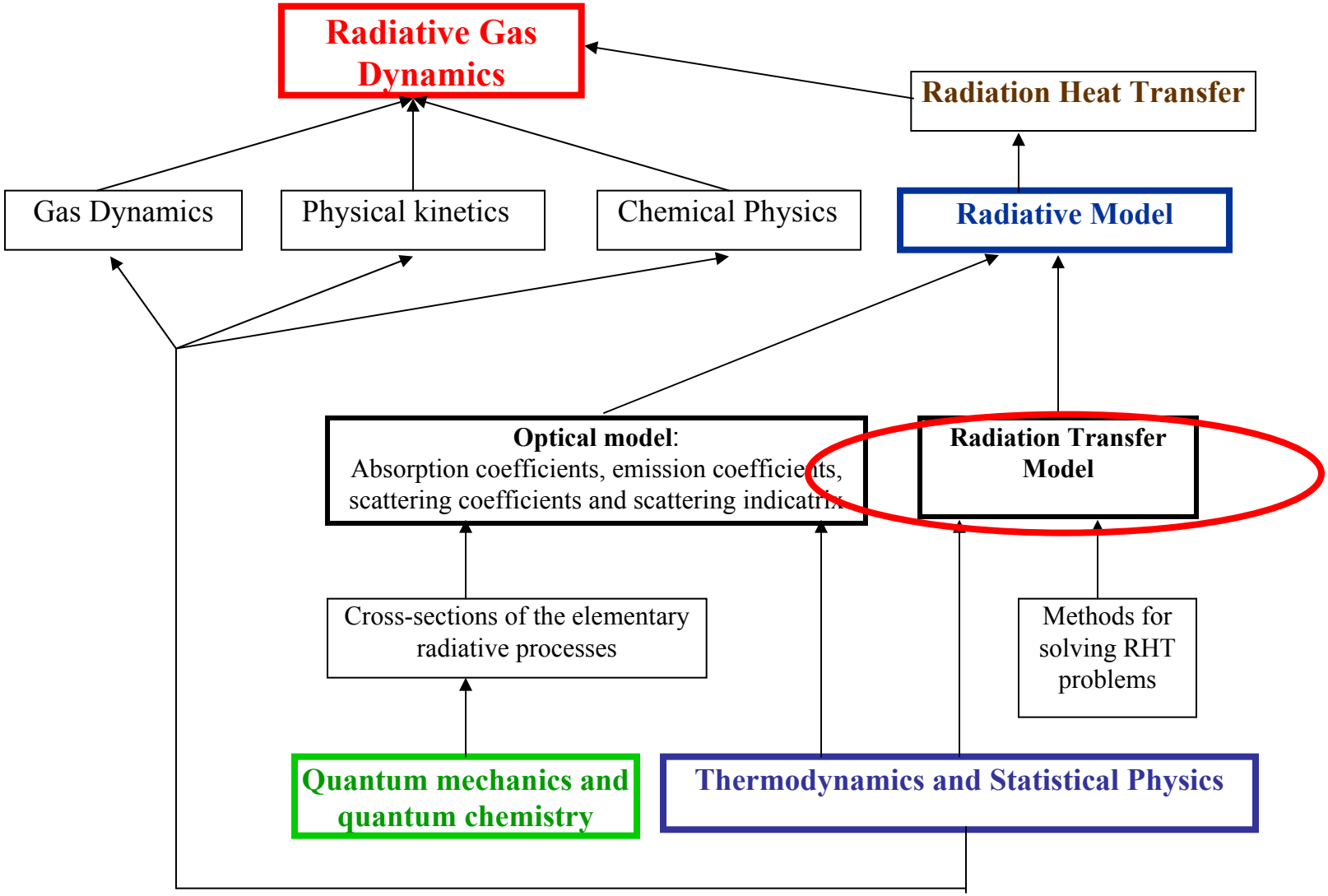
3. The full Radiation Heat Transfer equation must be solved for the following cases :

$$\tau_\omega \geq 0.2$$

Theoretical basis and general definitions:

Methods of the Radiation Heat Transfer Theory

Multi-Physics MHD/RadGD Numerical Simulation Models



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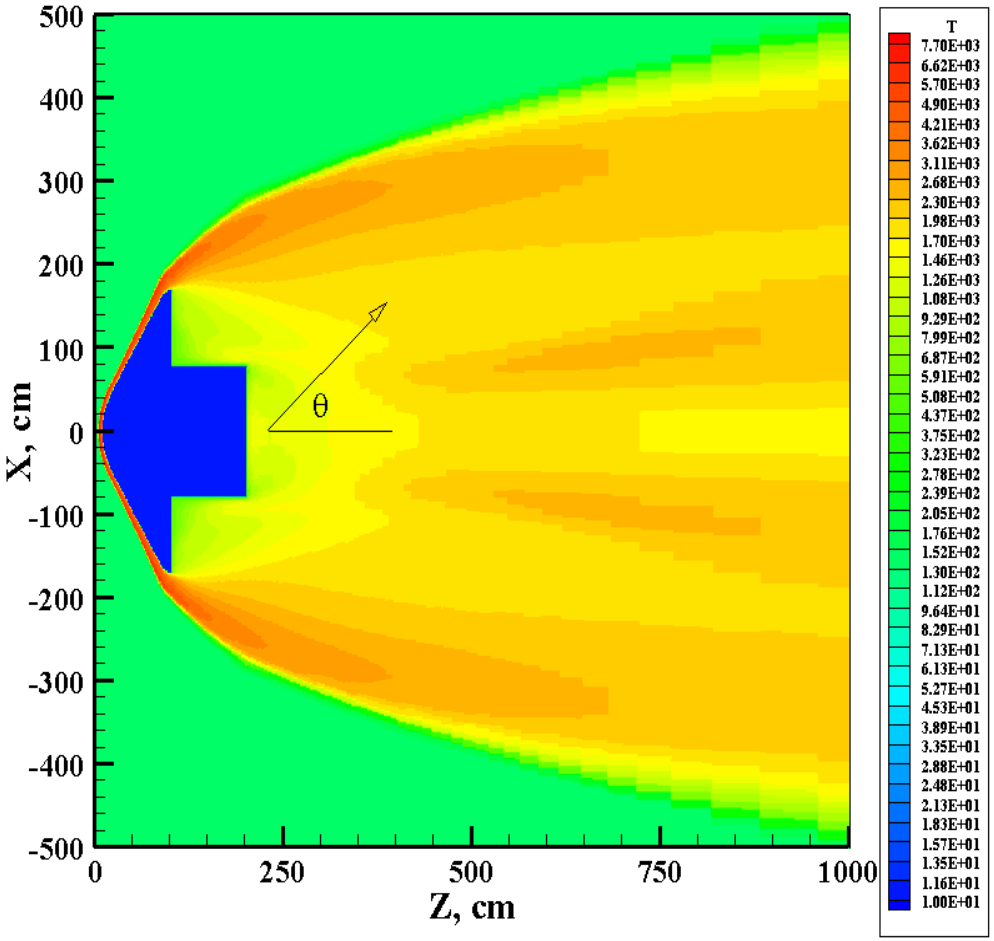
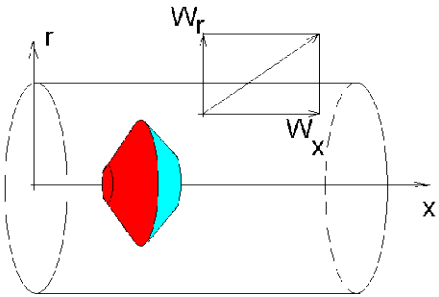
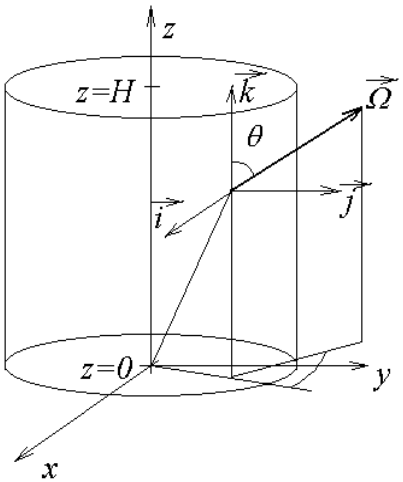
RHT methods for solving RadGD problems: The Spherical Harmonics method







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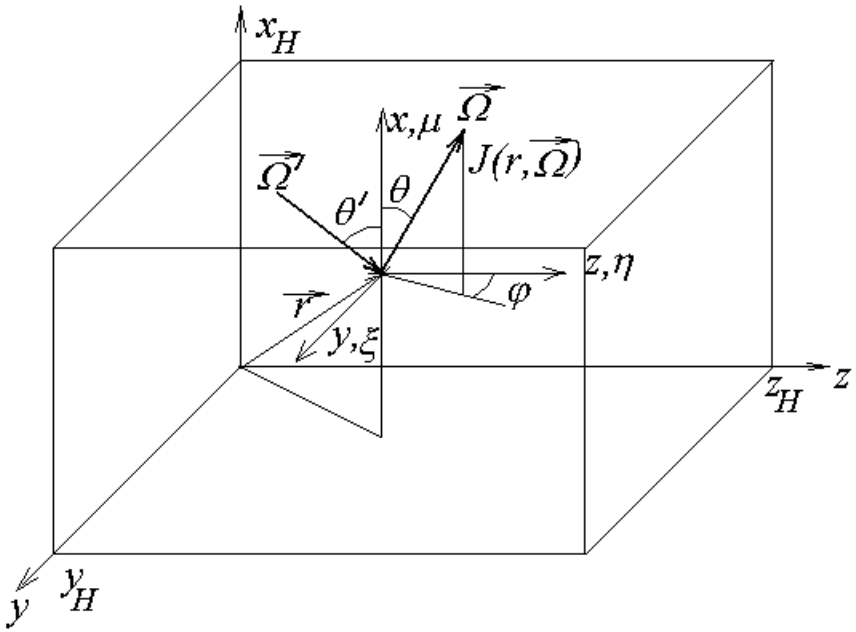
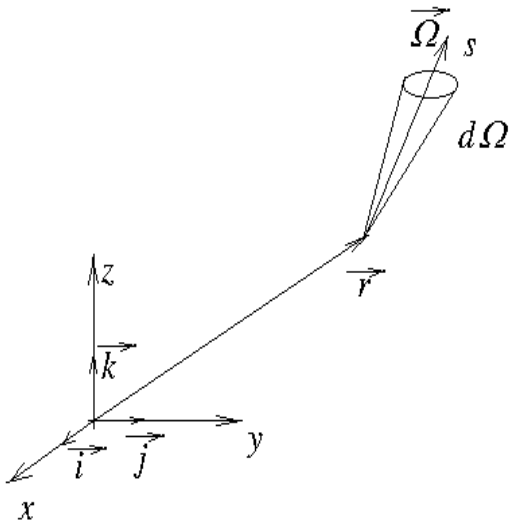
RHT methods for solving RadGD problems: The Discrete Ordinates method (DOM)





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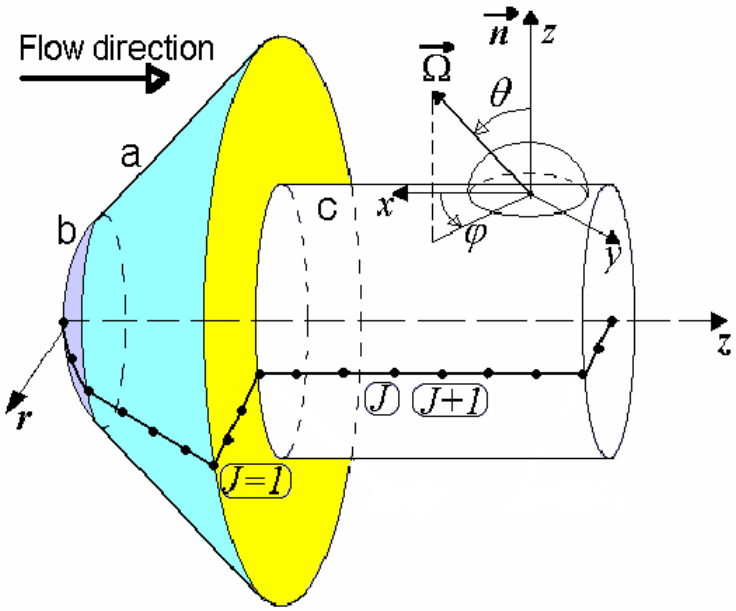
RHT methods for solving RadGD problems: The Ray-tracing method



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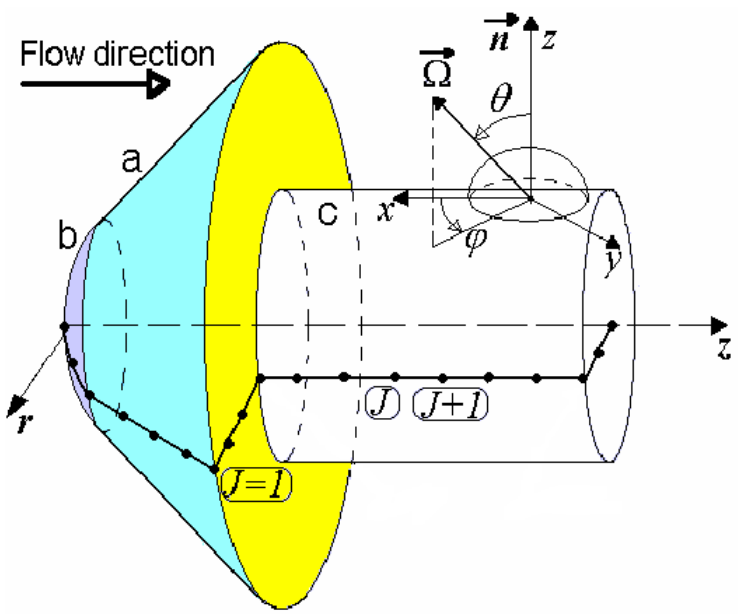
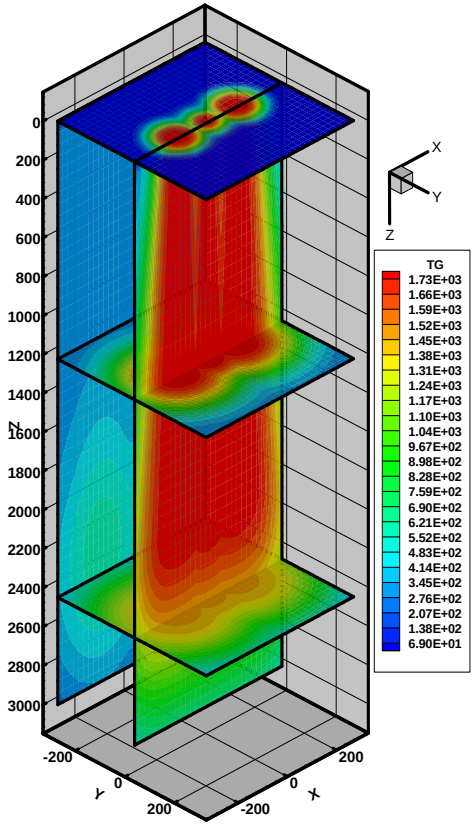
RHT methods for solving RadGD problems: The Monte-Carlo methods





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RHT methods for solving RadGD problems: The plane layer approach

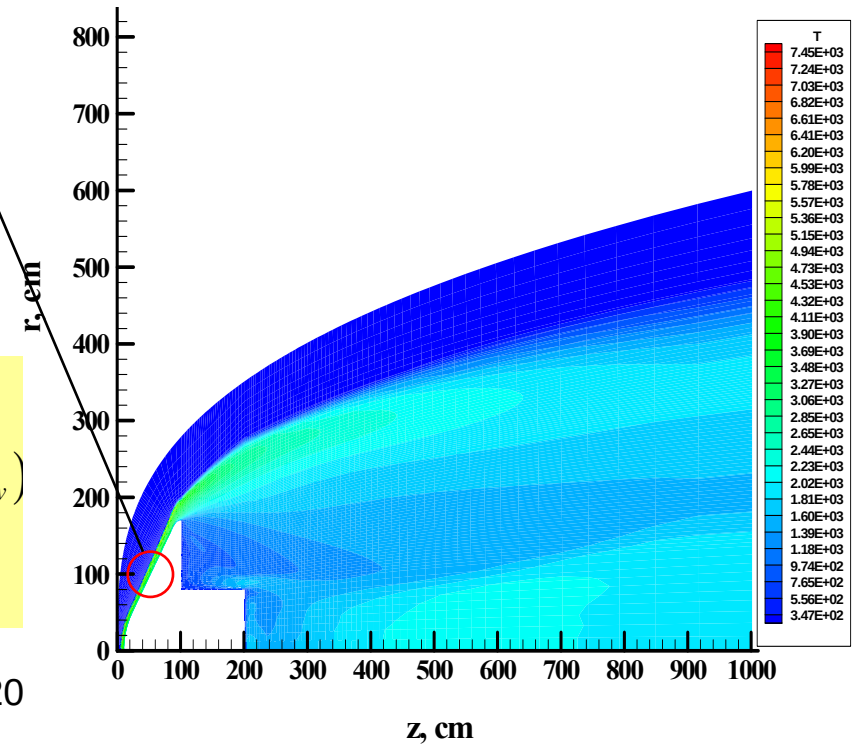
$$\pm\mu\frac{\partial J_\nu^{\pm}}{\partial x}+\beta J_\nu^{\pm}=J_{em,\nu}+\frac{\sigma_\nu}{2}\int_{-1}^{1}\gamma(\mu,\mu')\left[J_\nu^{+}(\mu')+J_\nu^{-}(\mu')\right]d\mu'$$

$$J_{em,\nu}=\kappa_\nu J_{b,\nu}$$

Boundary conditions are:

$$x=0,\ J_\nu^{+}(x=0,\mu)=r_0^s\,J_\nu^{-}(x=0,\mu)+\varepsilon_\nu J_{b,\nu}(x=0,T_w)$$

$$x=H,\ \ J_\nu^{-}(x=H,\mu)=0.$$



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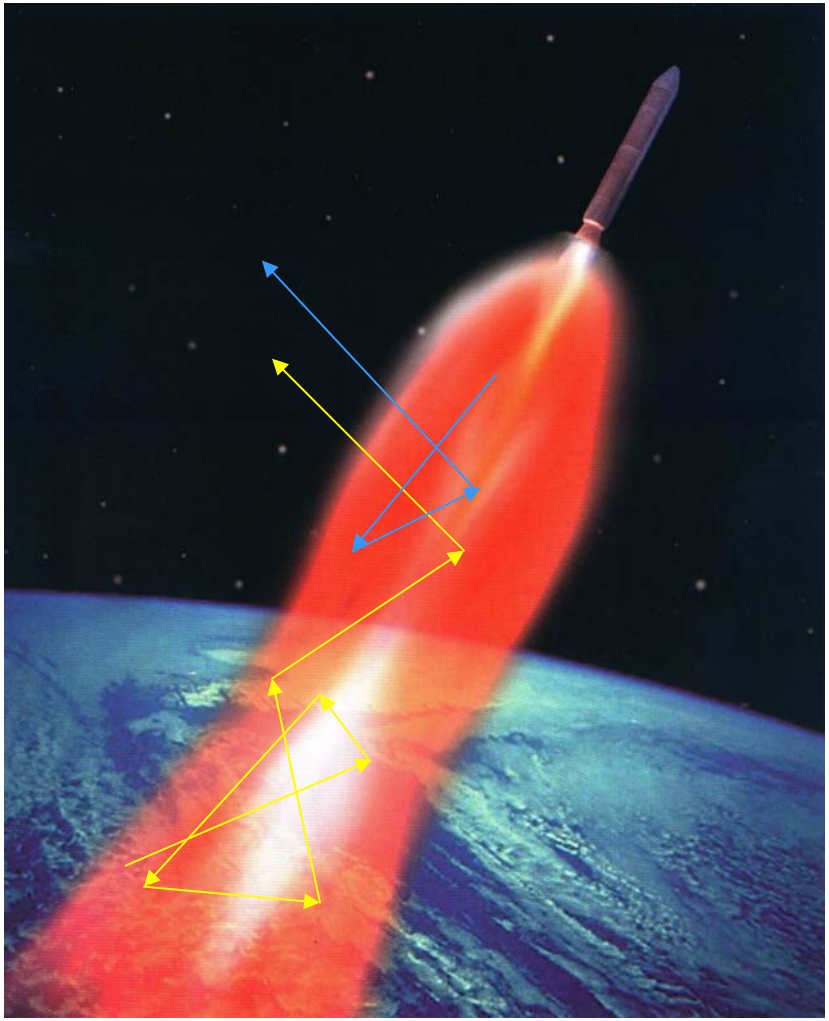
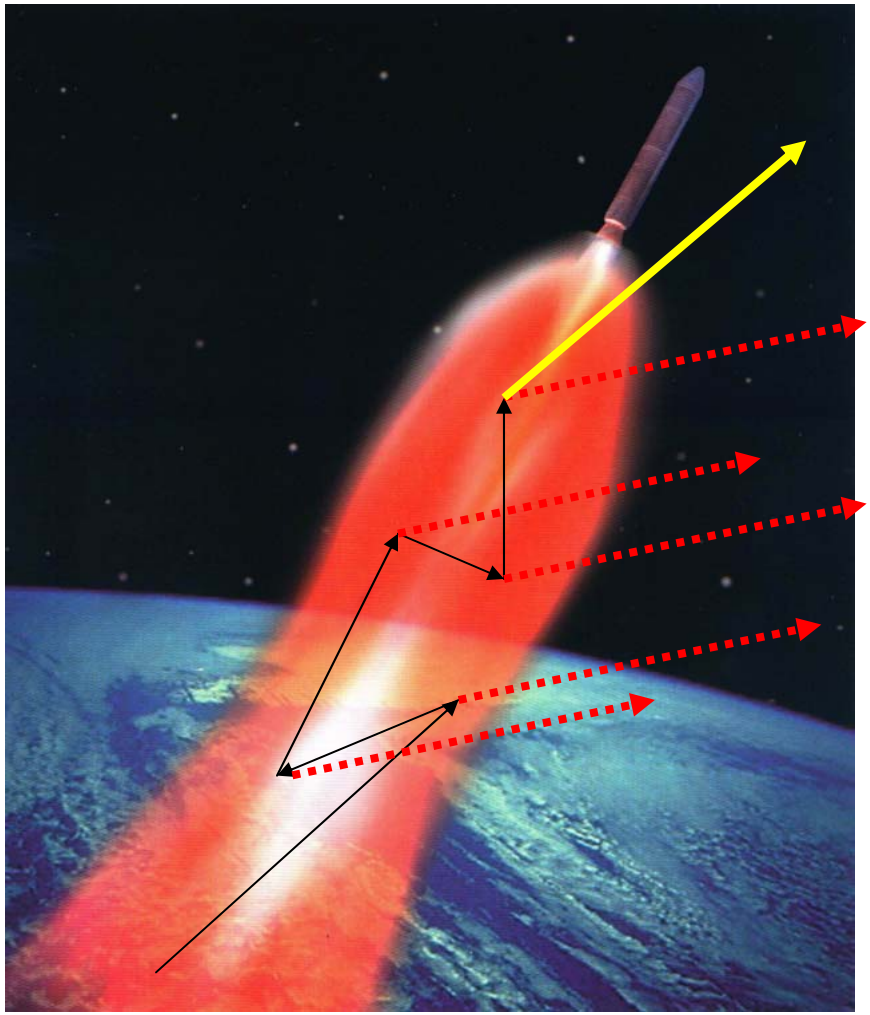
Regular Monte-Carlo algorithms of imitative simulation:



- Quasi-random numbers generation
- Calculation of angular variables of isotropic and non-isotropic unit vector
- Random estimation of initial coordinates of each photon group
- Photon group trajectory parameters prediction in non-uniform medium
- Photon group free path simulation
- Random estimation of collision processes of photon groups with particles of medium
- Random estimation of absorption and scattering
- Random events registration at imitating simulation of photon group trajectories
- Prediction of spectral emissivity
- Prediction of other characteristics of ragiation heat transfer (spectral heat fluxes, spectral density of radiation energy, total characteristics, etc.)
- Estimation of random errors

Multi-Physics MHD/RadGD Numerical Simulation Models

Local Estimation Monte-Carlo imitative algorithms



- Quasi-random numbers generation
- Calculation of angular variables of isotropic and non-isotropic unit vector
- Random estimation of initial coordinates of each photon group
- Photon group trajectory parameters prediction in non-uniform medium
- Photon group free path simulation
- Random estimation of collision processes of photon groups with particles of medium
- Random estimation of absorption and scattering
- **Spectral directional emissivity estimation at EACH random event**
- Prediction of spectral emissivity
- Prediction of other characteristics of ragiation heat transfer (spectral heat fluxes, spectral density of radiation energy, total characteristics, etc.)
- Estimation of random errors

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RHT theory methods: Summary

1. The Spherical Harmonics method can be used for determination div$\mathbf{W}_{\mathbf{Rad}}$

2. The plane layer approach is very effective method for strong radiative-gasdynamic interaction problems (1D)

3. The Discreet Ordinates method can be used for solving 2D and 3D line-by-line problems of RHT

4. The Ray-Tracing method can be used for solving RHT problems in 2D and 3D geometries together with Random Models of Atomic and Molecular lines

5. The Monte-Carlo method is most universal one for solving RHT problems

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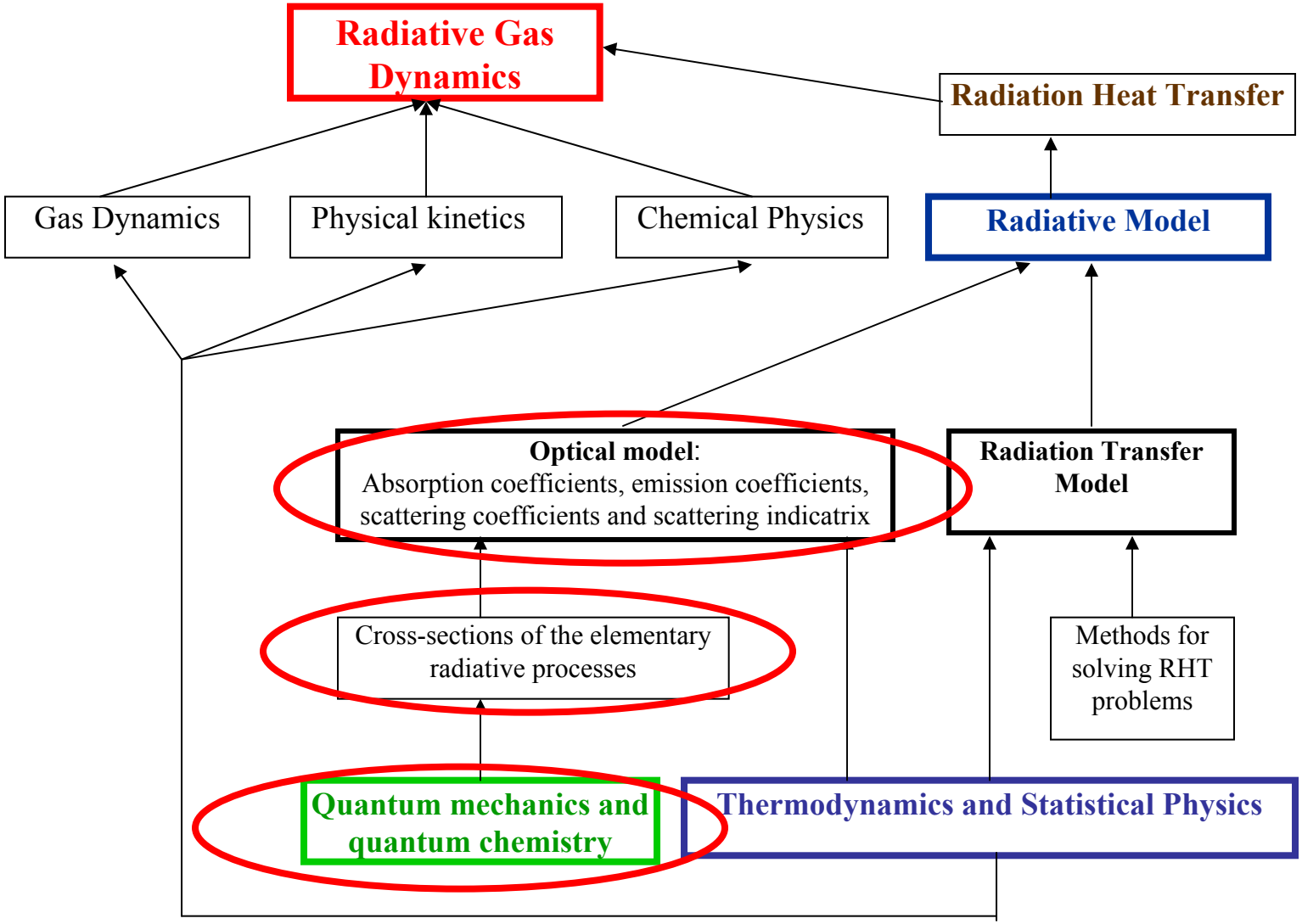
Theoretical basis and general definitions

Spectral optical models

Multi-Physics MHD/RadGD Numerical Simulation Models



Numerical simulation models for prediction of spectral optical properties

ASTEROID is the computer code which is intended for prediction of spectral optical properties of heated gases and plasmas with the use of quasi-classical and quantum ab-initio approaches

ASTEROID can be incorporated into CFD/RadGD/MHD codes with the purpose of the "on-line" prediction of spectral optical properties inside RadGD coupled numerical simulation procedures

ASTEROID: H, He, C, N, O, Ar, Fe, Si, …;
Air, H_2, H_2+He, CO_2+N_2+Ar+O_2, Air+H_2O, Air+Ar, Air+CO_2+H_2O, Air+SiO_2 , …

ASTEROID: T<100 – 20 000 – 120 000 K , P< 1000 atm

ASTEROID: Non-equilibrium chemical compositions, LTE, Non-LTE conditions

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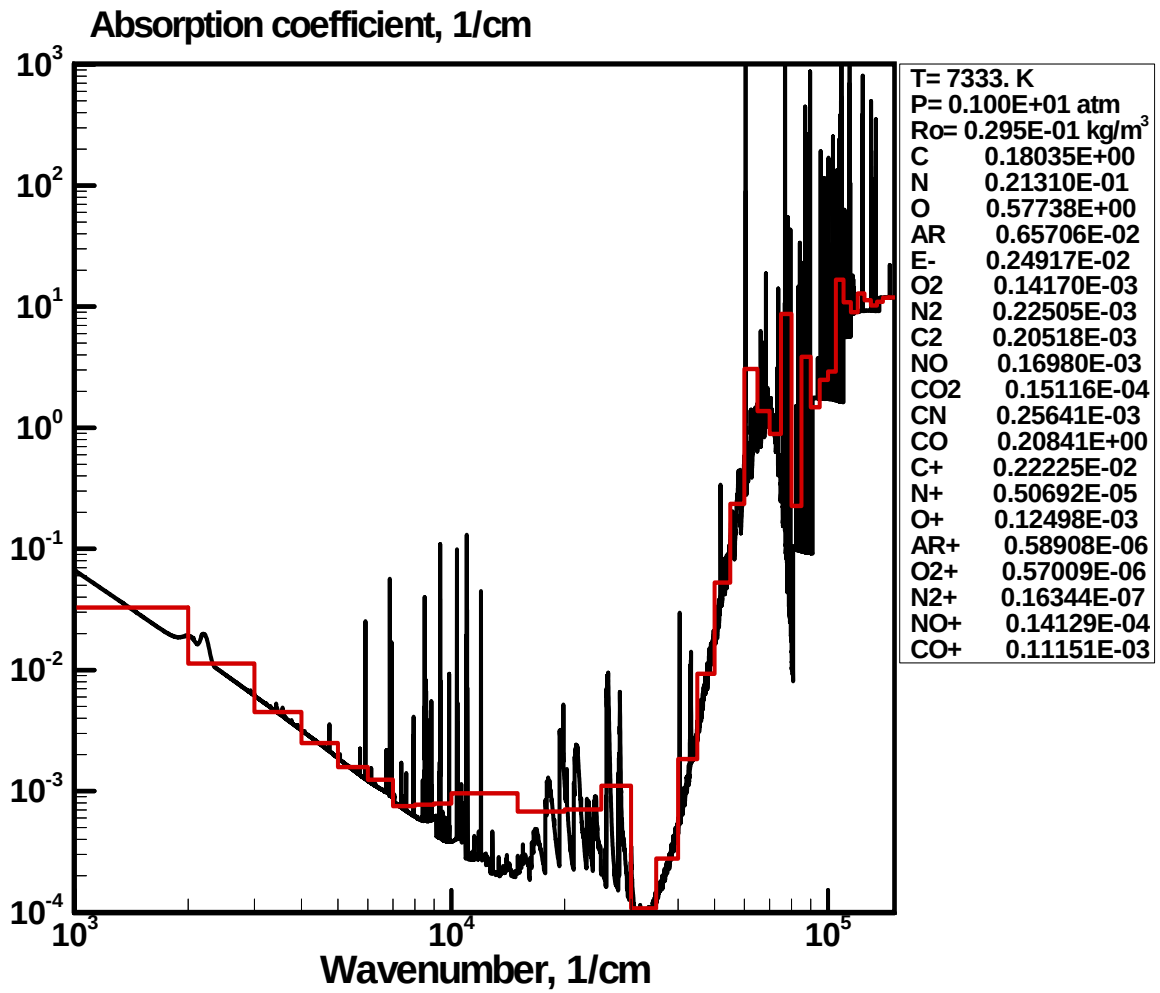
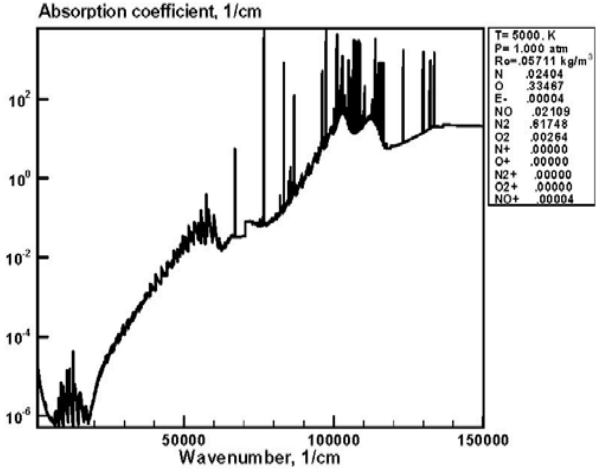
Examples of calculations with the use of ASTEROID code

- Spectral (line-by-line) and group absorption coefficient of CO_2(97%)- N_2(3%) at T=7333 K, p=1 атм
- Line-by-line calculation: $3 \cdot 10^6$ spectral points

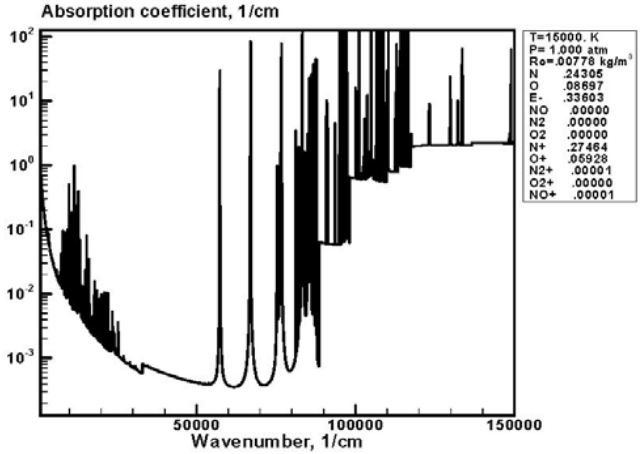


Multi-Physics MHD/RadGD Numerical Simulation Models

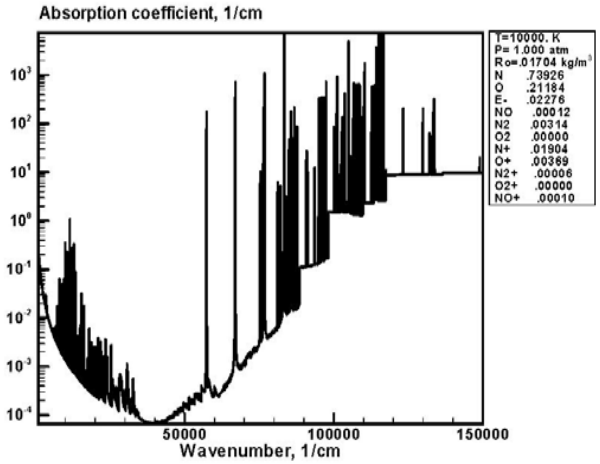
ASTEROID: Spectral absorption coefficients of air at different temperatures



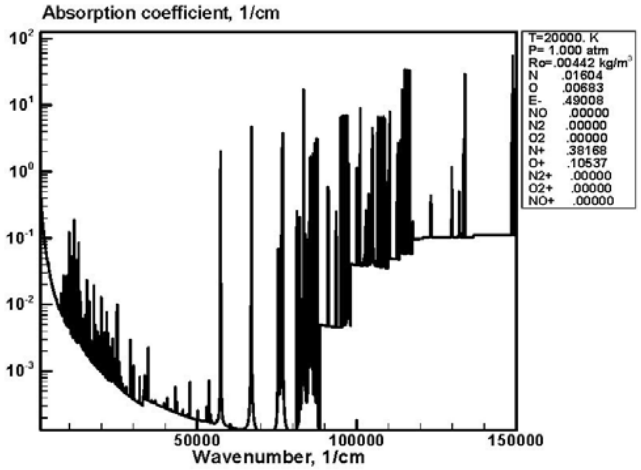
Spectral absorption coefficient of low-temperature air plasma at p =1 atm and T =5000 K



Spectral absorption coefficient of low-temperature air plasma at p =1 atm and T =15000 K



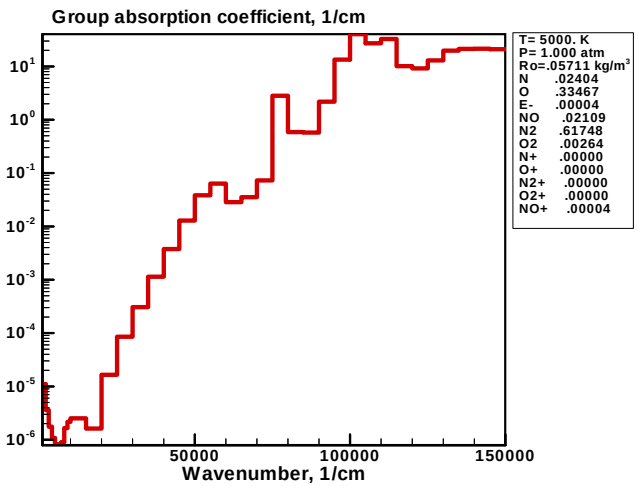
Spectral absorption coefficient of low-temperature air plasma at p =1 atm and T =10000 K



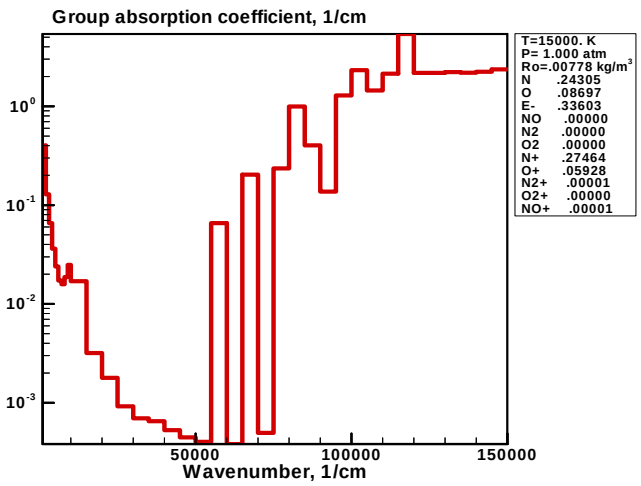
Spectral absorption coefficient of low-temperature air plasma at p =1 atm and T =20000 K

Multi-Physics MHD/RadGD Numerical Simulation Models

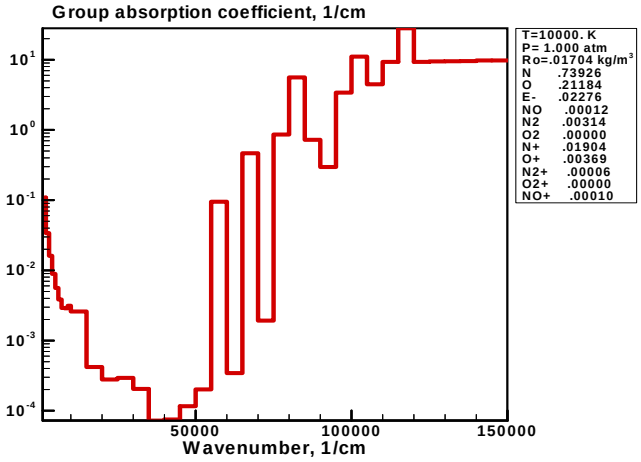
ASTEROID: Group absorption coefficients of air at different temperatures



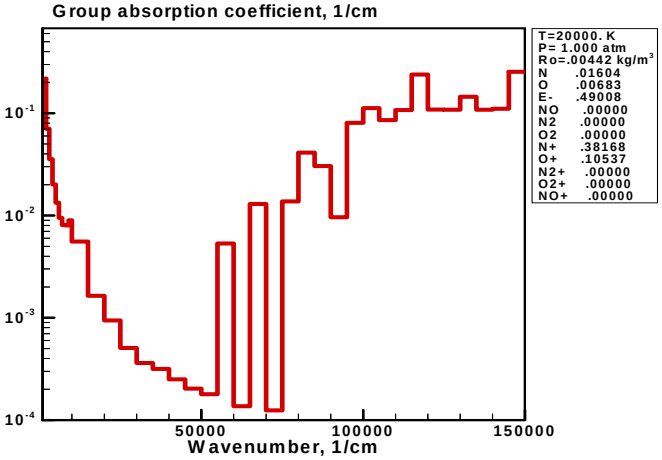
Group absorption coefficient of low-temperature air plasma at p = 1 atm and T = 5000 K



Group absorption coefficient of low-temperature air plasma at p = 1 atm and T = 15000 K



Group absorption coefficient of low-temperature air plasma at p = 1 atm and T = 10000 K

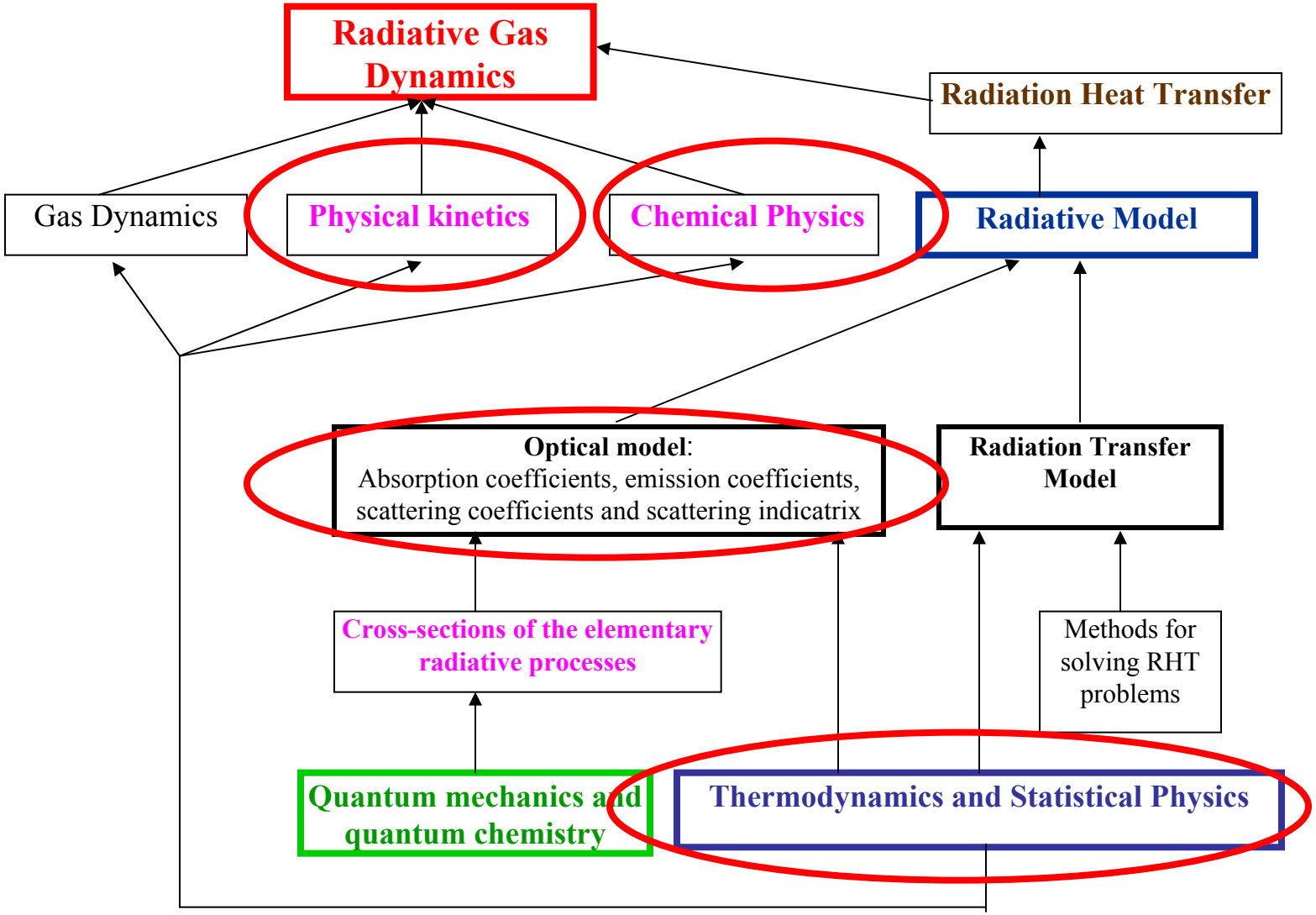


Group absorption coefficient of low-temperature air plasma at p = 1 atm and T = 20000 K

Theoretical basis and general definitions

Physical-chemical kinetics

Multi-Physics MHD/RadGD Numerical Simulation Models



LTE and non-LTE processes in atomic and molecular plasma

General conditions for LTE

$$\frac{dn(v)}{n} = \frac{4}{\sqrt{\pi}}\left(\frac{m}{2T}\right)^{3/2} \exp\left(-\frac{mv^2}{2T}\right) v^2 dv$$

$$\frac{n_k}{n_l} = \frac{g_k}{g_l}\exp\left(-\frac{\Delta E_{kl}}{T}\right)$$

$$n_k = n_\Sigma \frac{g_k}{Q_\Sigma}\exp\left(-\frac{E_1 - E_k}{T}\right)$$

$$Q_\Sigma = \sum_k g_k \exp\left(-\frac{E_1 - E_k}{T}\right)$$

$$\frac{n_e n_i}{n_a} = 2\frac{Q_i}{Q_a}\left(\frac{2\pi m T}{k^2}\right)^{3/2} \exp\left(-\frac{E_1}{T}\right)$$

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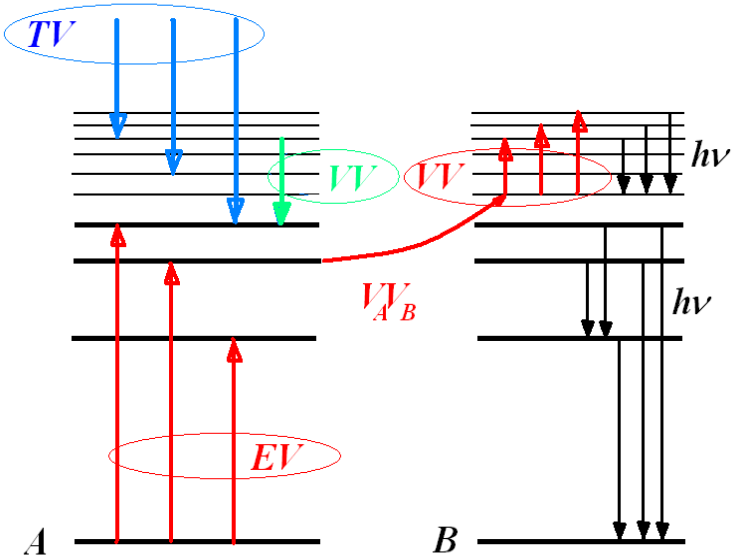
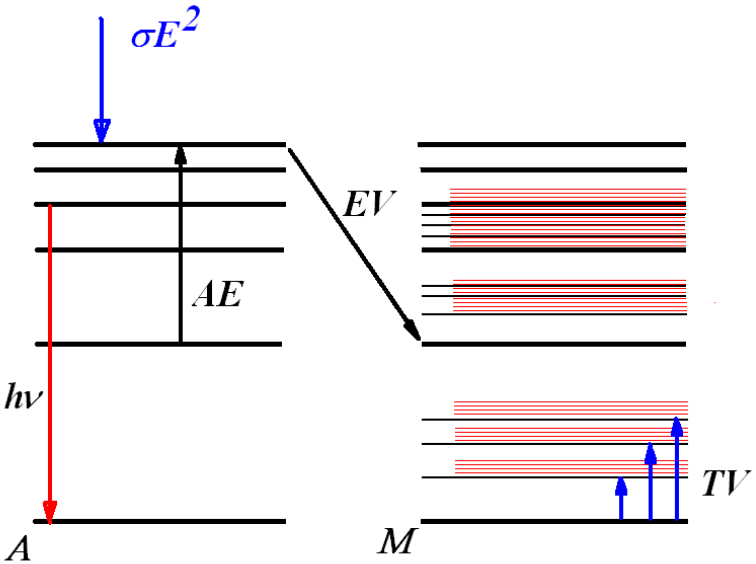
Quasi-Thermodynamic Models

Some non-equilibrium processes for molecular and atomic plasma





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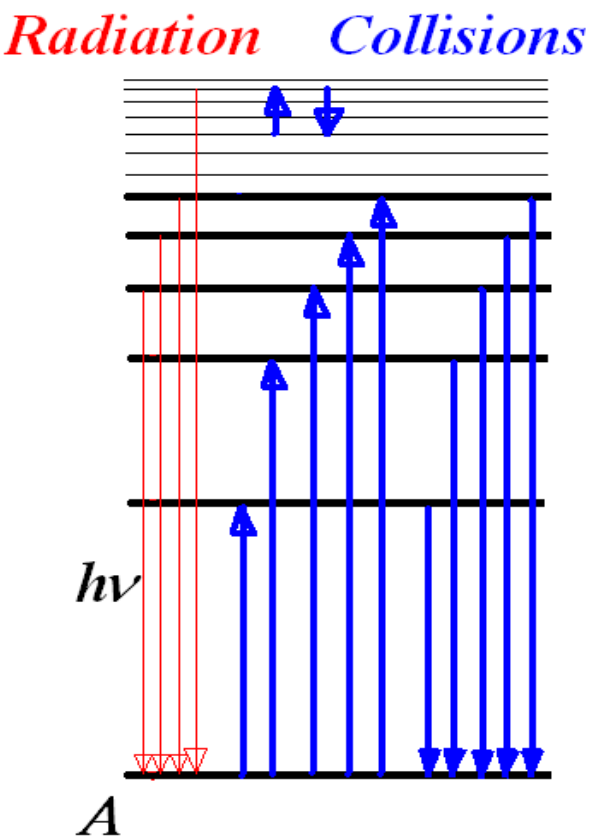
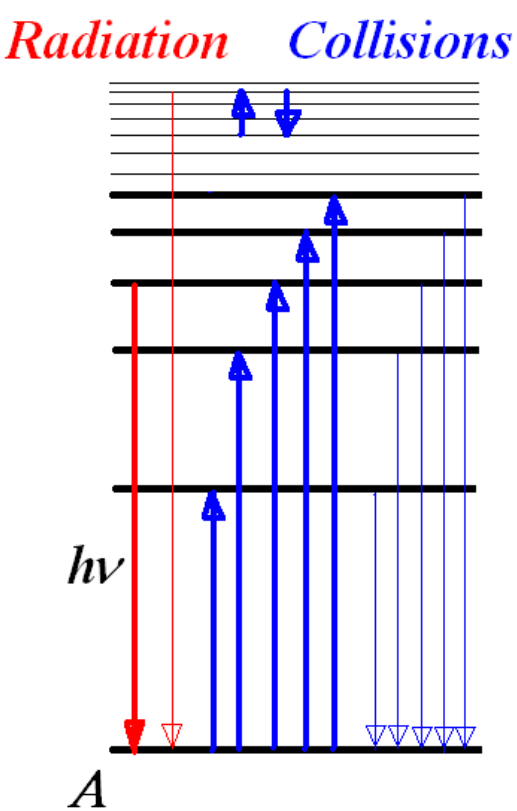
Quasi-Thermodynamic Models

The Local Thermodynamic Equilibrium model

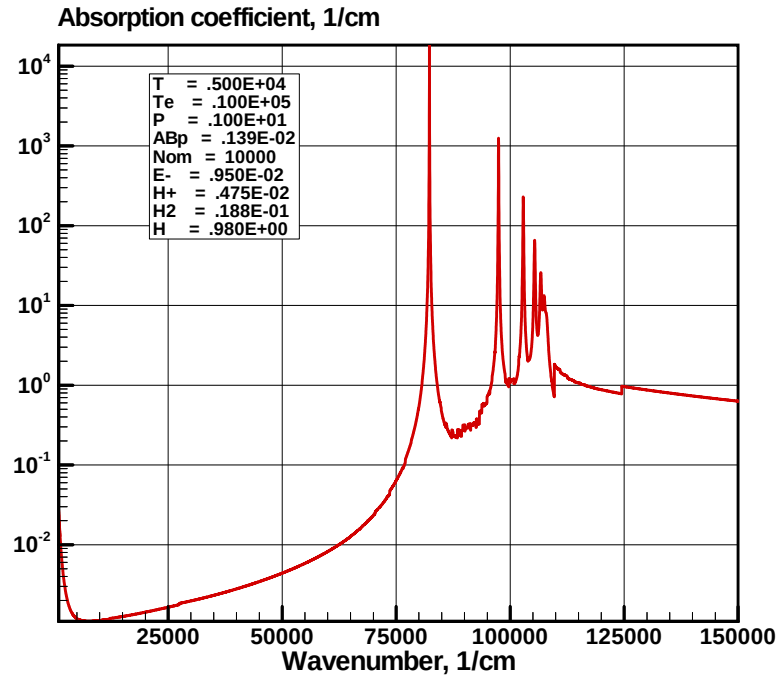


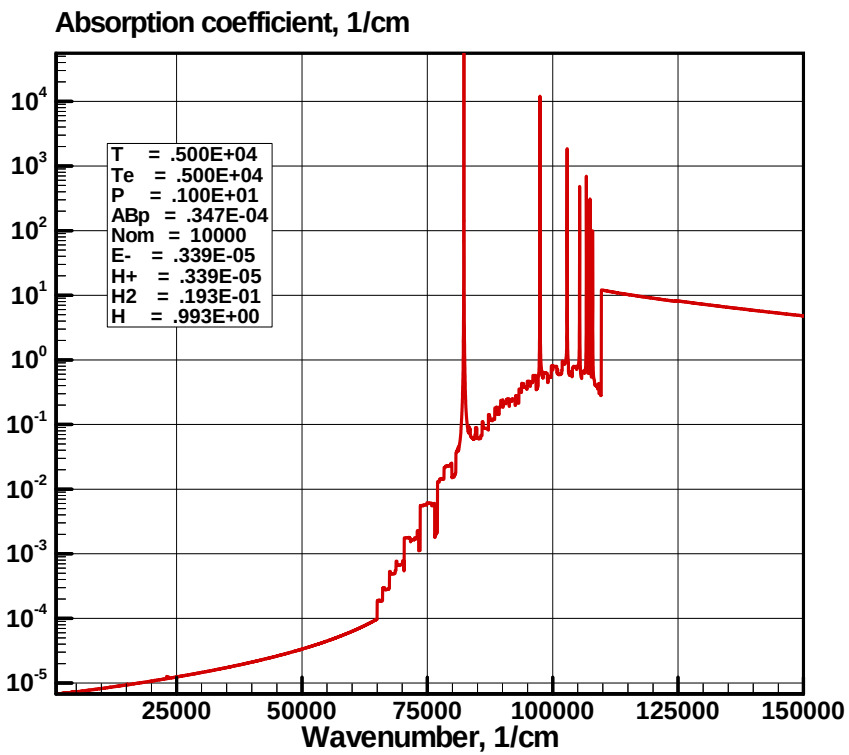
The Coronal model



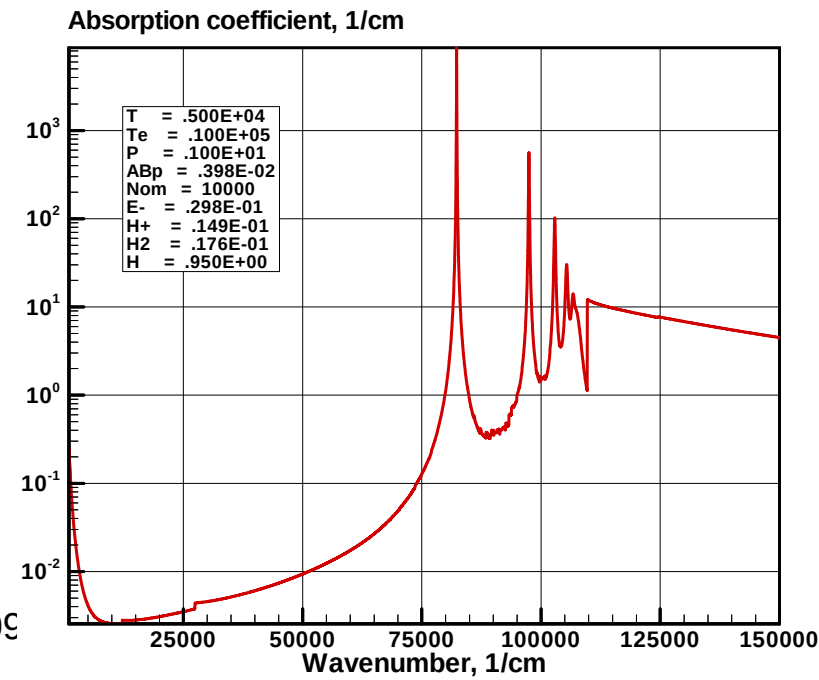
SPECTRAL OPTICAL PROPERTIES OF NONEQUILIBRIUM HYDROGEN PLASMA

Free energy minimization →



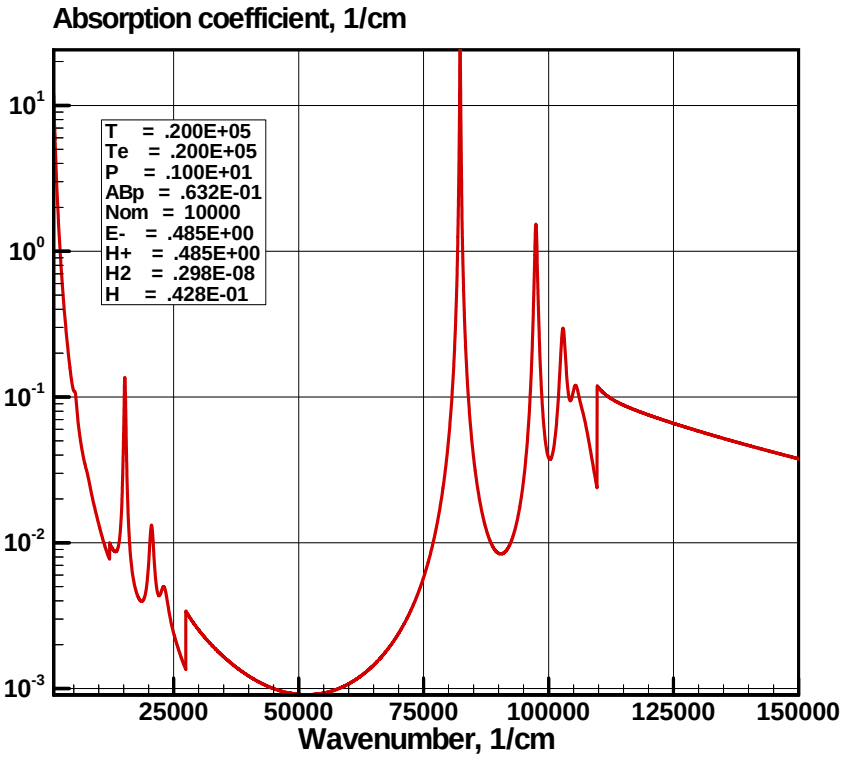


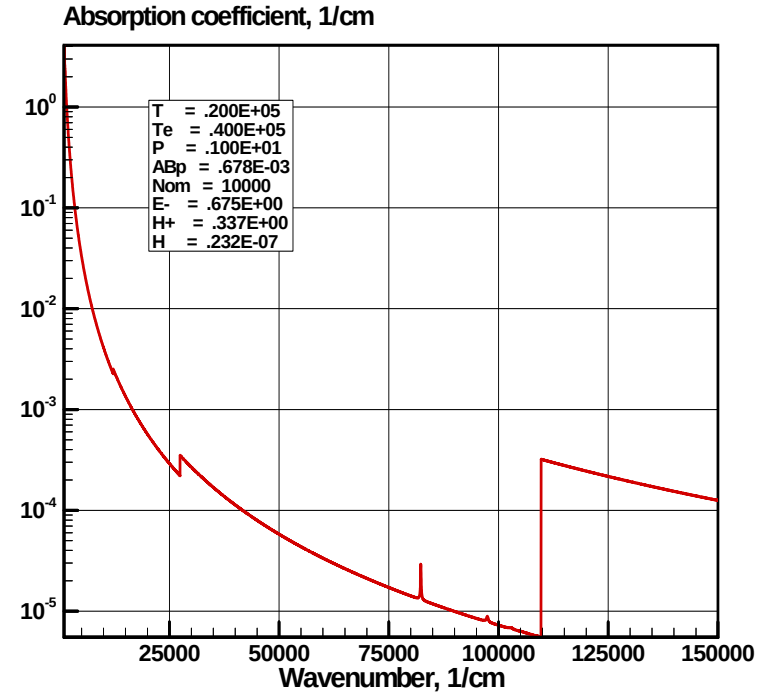
Entropy maximization →



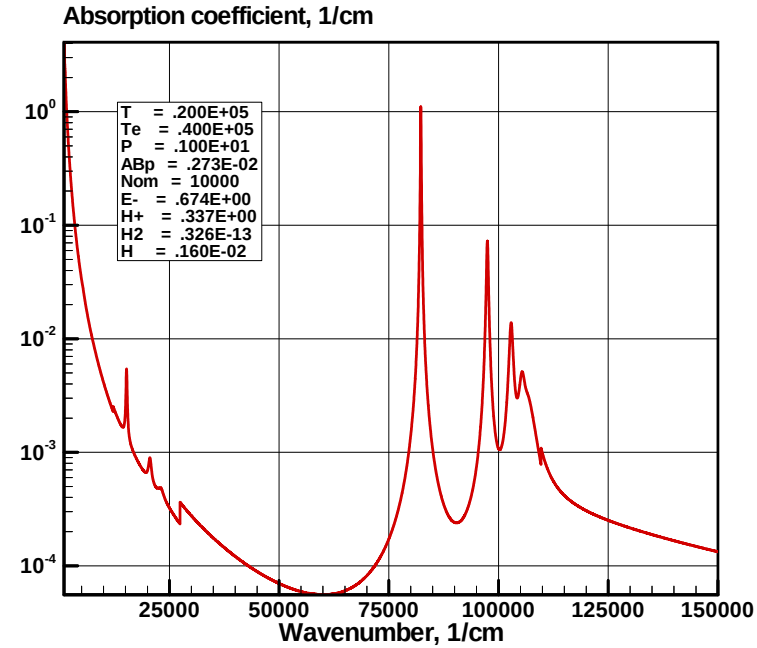
SPECTRAL OPTICAL PROPERTIES OF NONEQUILIBRIUM HYDROGEN PLASMA

Free energy minimization →





Entropy maximization →



Theoretical basis and general definitions

Radiative Gas Dynamics

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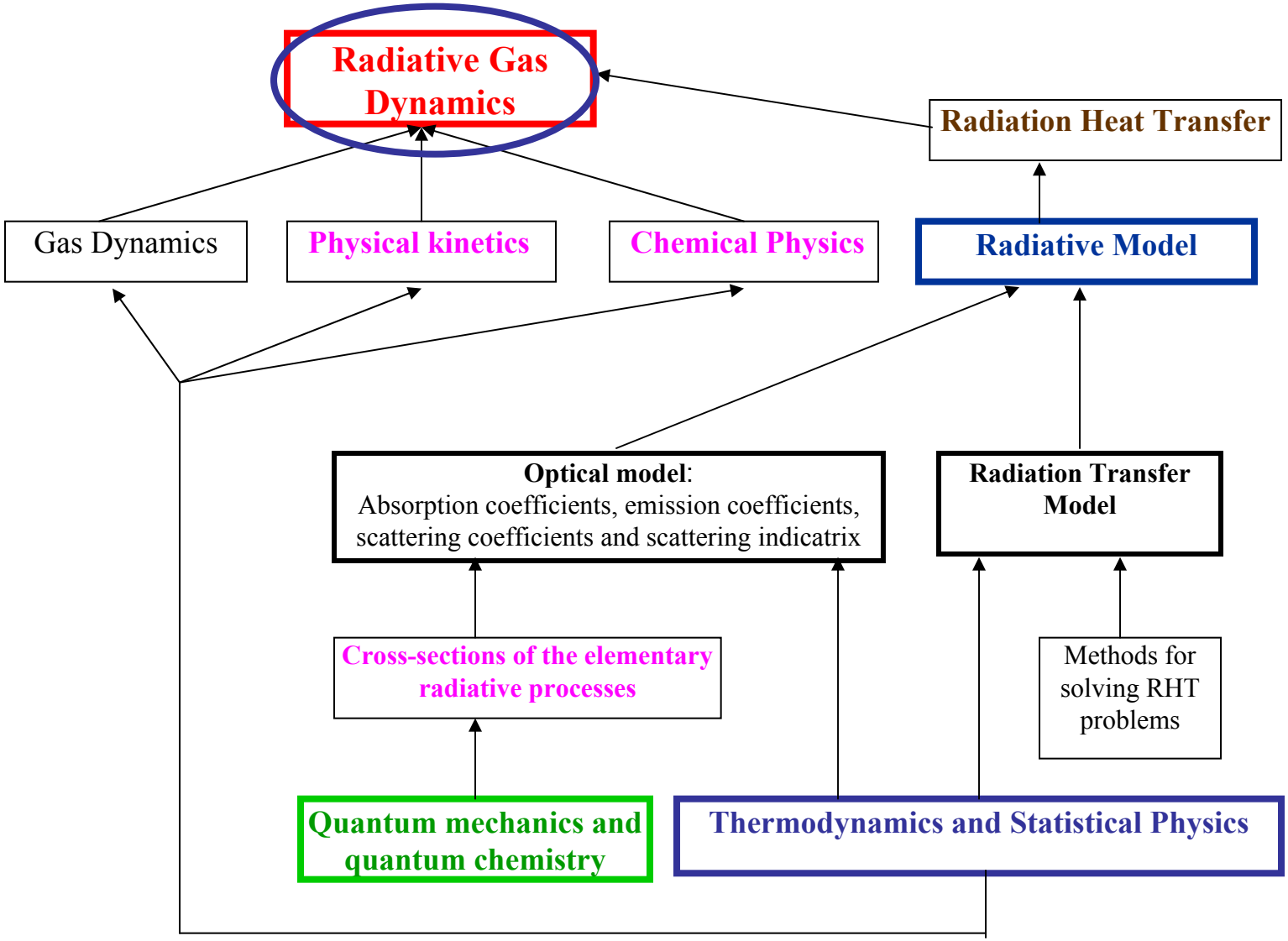

Multi-Physics MHD/RadGD Numerical Simulation Models

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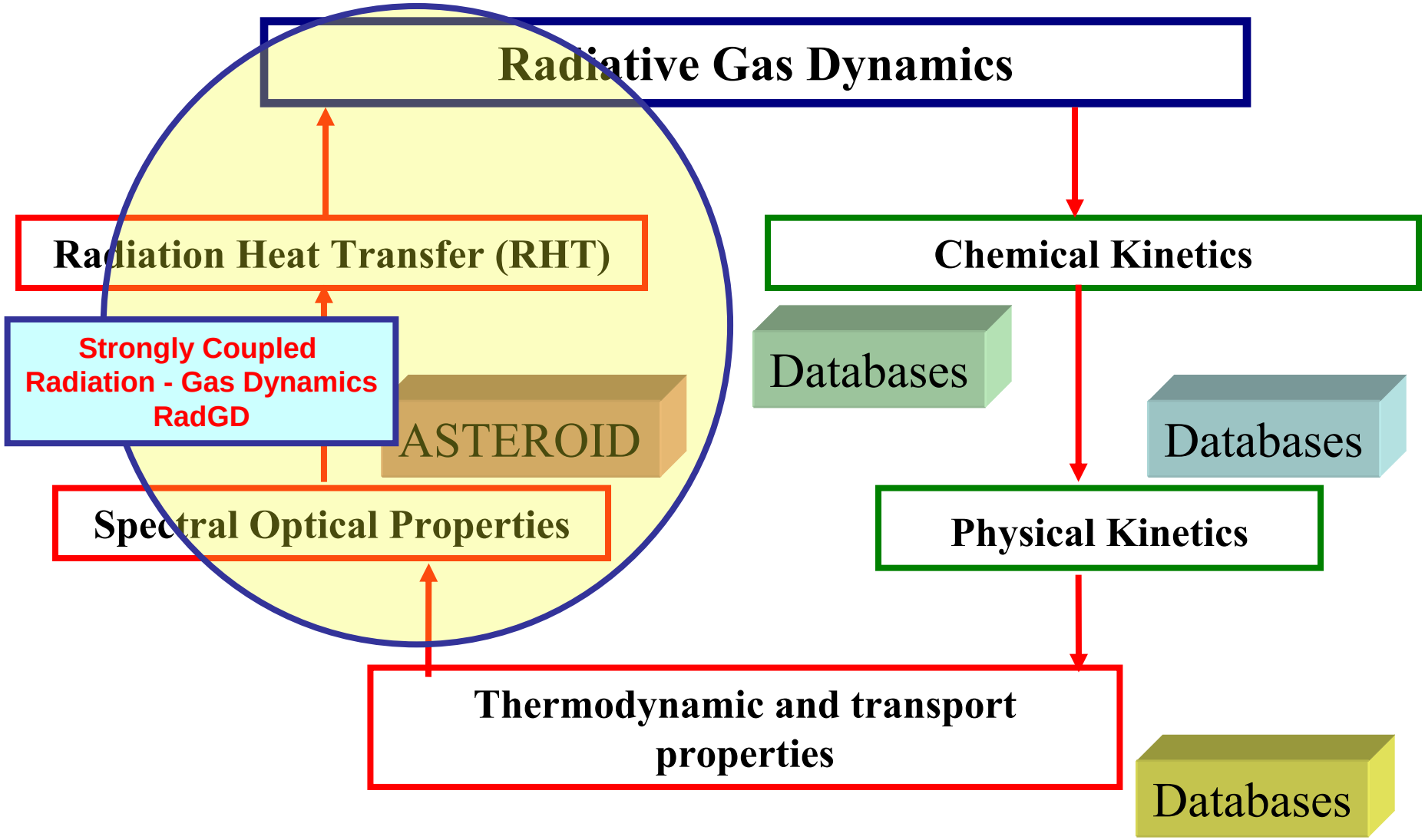
Schematic representation of general elements of RadGD codes with strong radiative gasdynamic interaction

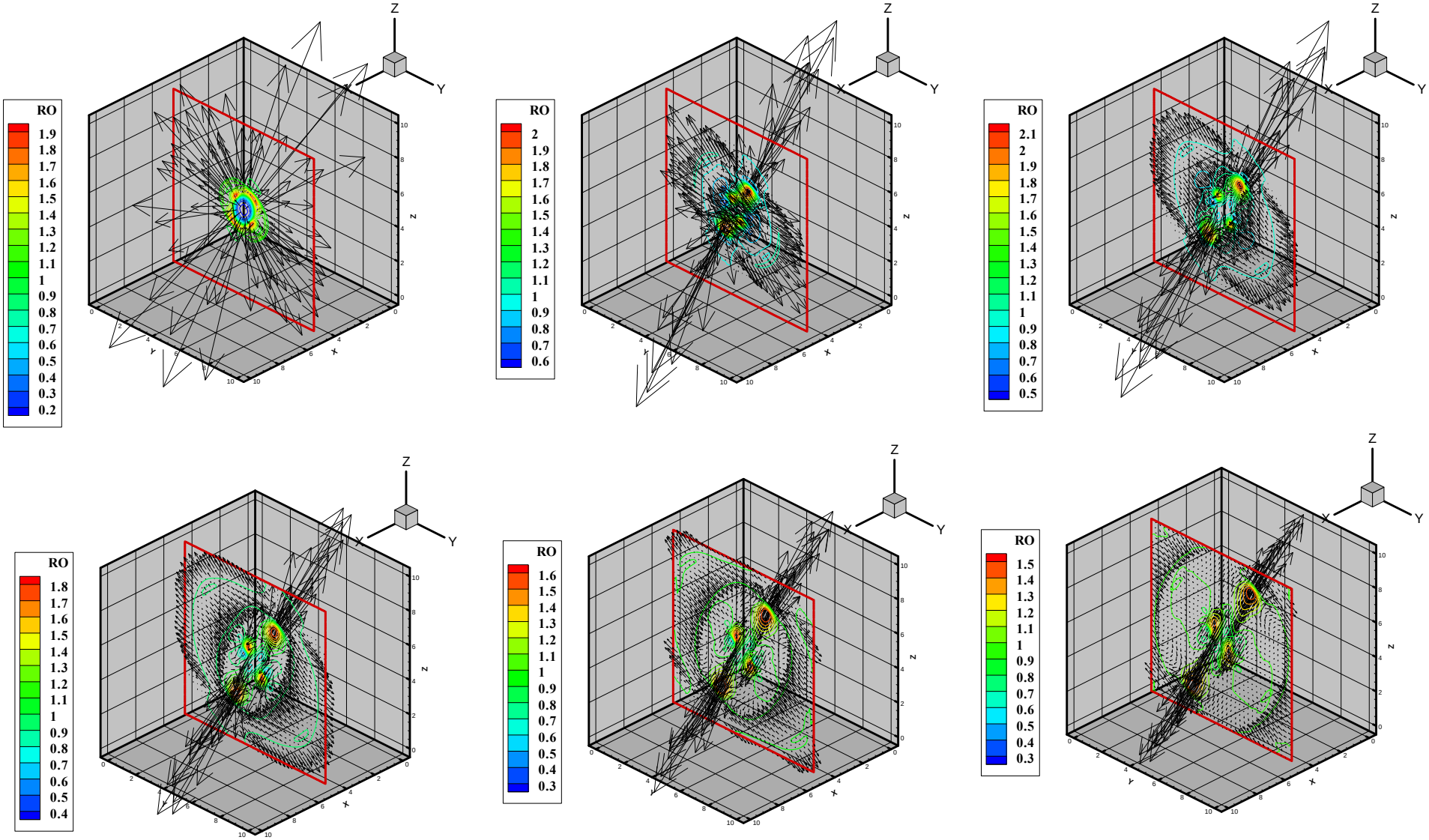


RadGD/MHD: The "classical" multi-physics problems for aerospace applications

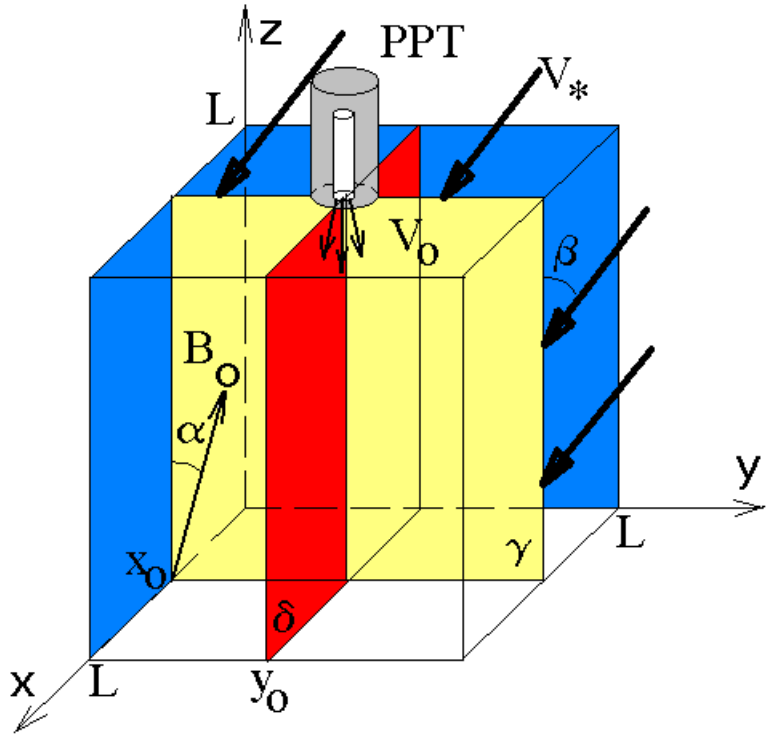
- Shock wave structure
- Plumes and nozzles
- Hypersonic boundary layer
- Internal and external plasmadynamics
- Entry and re-entry problems
- Structure of shock layer
- Explosions (Non-stationary RadGD)
- High energy beams (laser, ions, electrons) interaction with matter

Multi-Physics MHD/RadGD Numerical Simulation Models

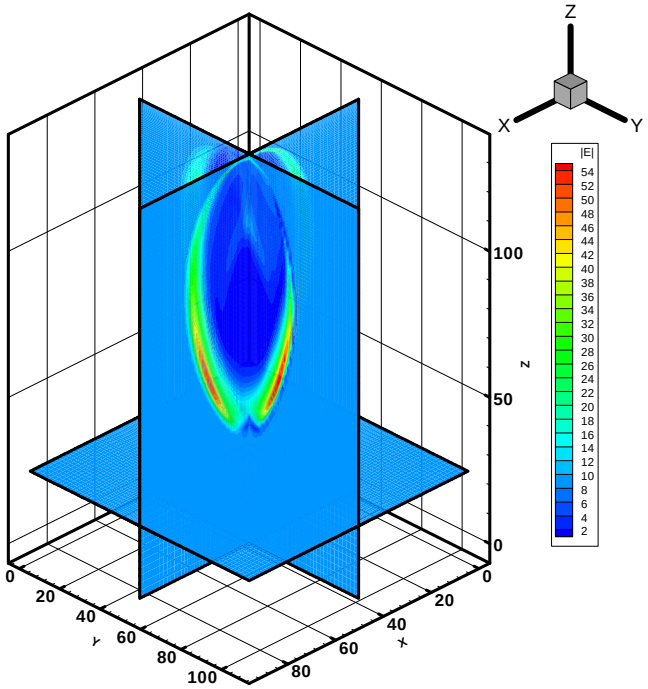
MHD expansion of ionizing gas in ionosphere



Multi-Physics MHD/RadGD Numerical Simulation Models



- 3D MHD interaction of PPT plasma plume with ambient ionosphere



Generation of the electric field

$$\rho_* = 2.0 \cdot 10^{-9} \ \ кг/м^3, \quad p_* = 4.49 \cdot 10^{-4} \ \ Па$$

$$B_0 = 5 \cdot 10^{-5} \ T, \quad \alpha_{B \wedge Y} = 30^0$$

$$V_* = -6.0 \ \ км/с, \quad \vartheta_{V_{\inf}} = 30^0$$

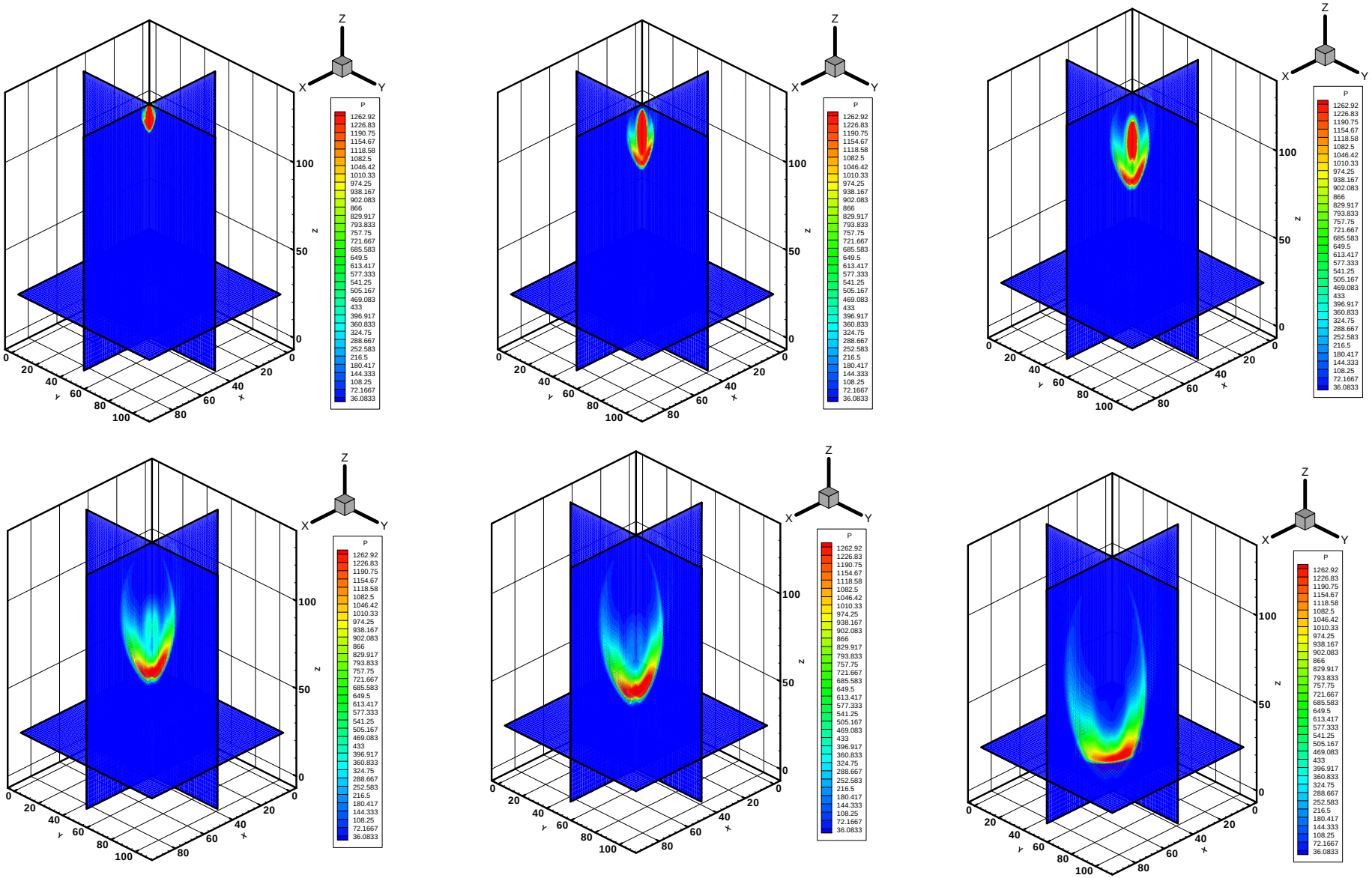
$$V_{pl} = -25 \ \ кг/с, \quad \rho_{pl} = 2.0 \cdot 10^{-7} \ \ кг/м^3,$$

$$p_{pl} = 20 \ Па, \quad R_{ex} = 0.03 \ м$$

$$T_{HPT} = 6 \ \mu s, \quad T_{simulation} = 70 \ \mu s$$

Multi-Physics MHD/RadGD Numerical Simulation Models

3D MHD interaction of PPT plasma plume with ambient ionosphere



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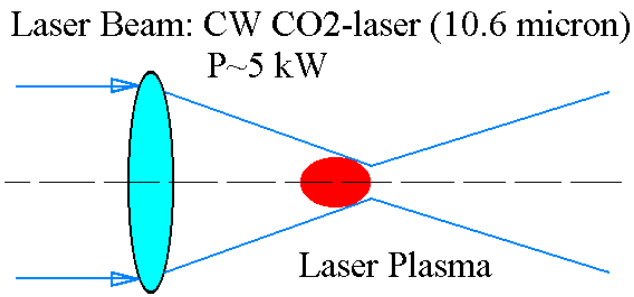
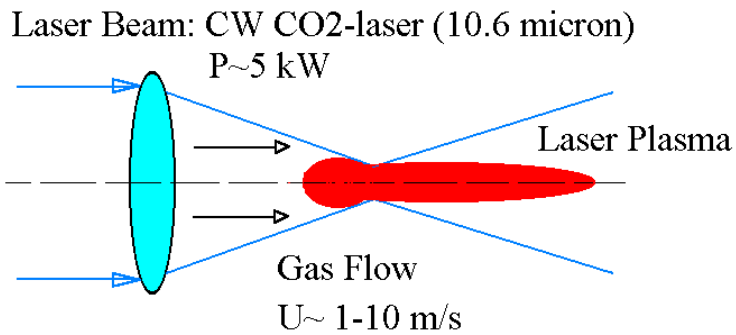
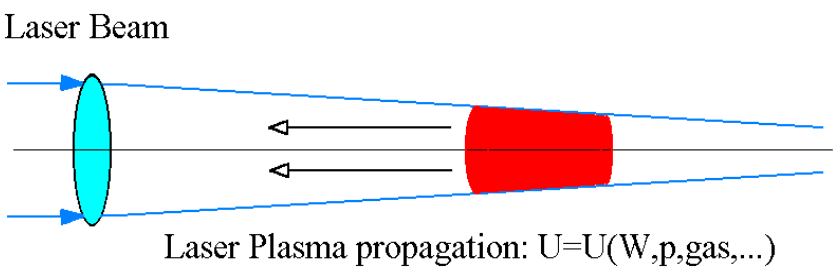
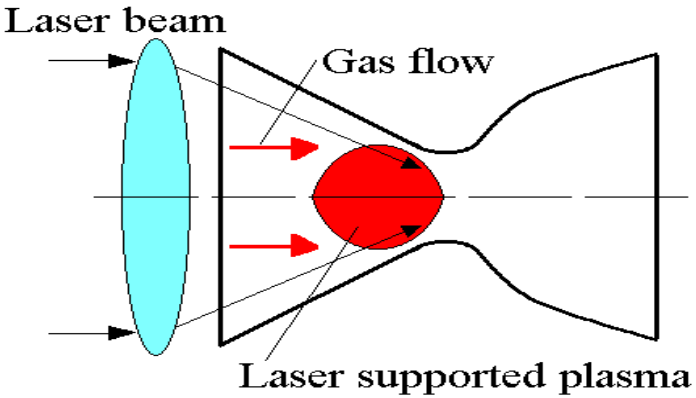
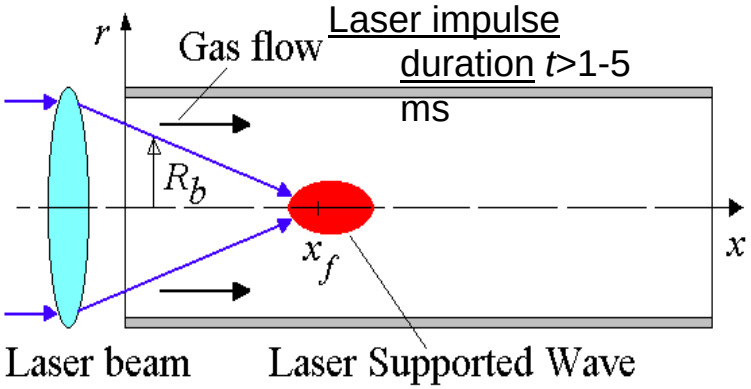
Laser supported waves











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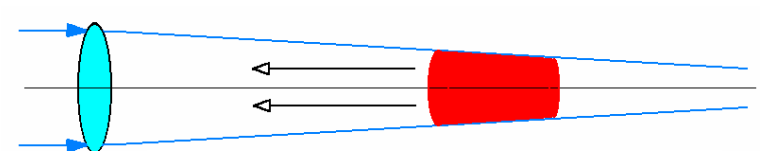
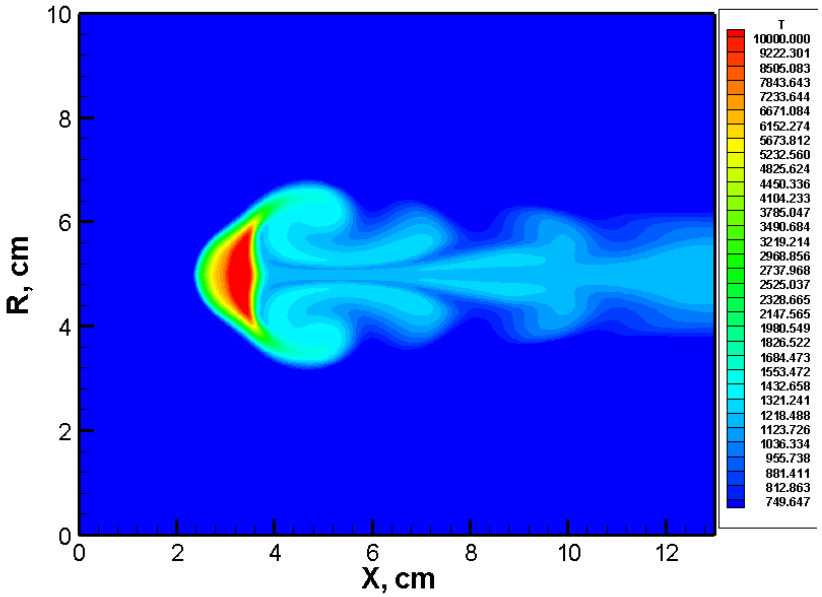
RadGD of laser supported waves: gas dynamic instabilities



- Navier-Stockes equations
- Model of turbulent mixture
- The 11th species composition
- Chemical reactions
- Multi-group radiation model



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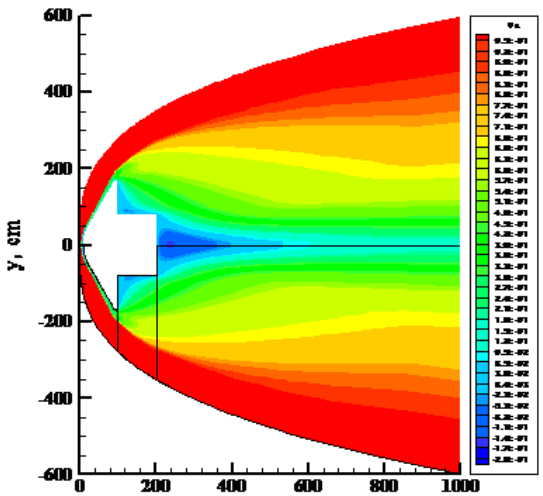
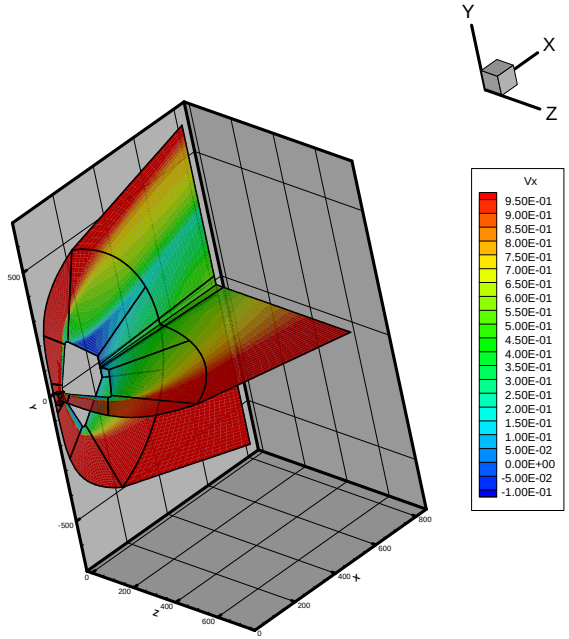
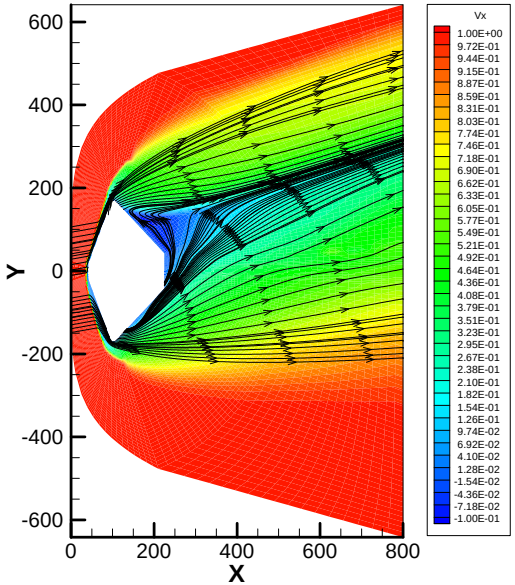
Aerophysics:

computer code NERAT (Non-Equilibrium Radiative Aero-Thermodynamics)

- NERAT-2D – two dimensional plane and axially symmetric
- NERAT-3D – three dimensional
- Structured multi-block grids
- Laminar and turbulent regimes
- Physical-chemical kinetics
- Radiation heat transfer + Spectral optical properties (ASTEROID code)







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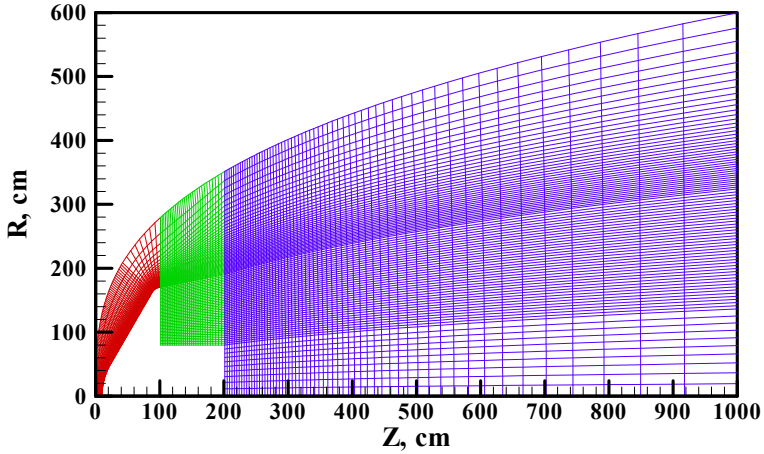
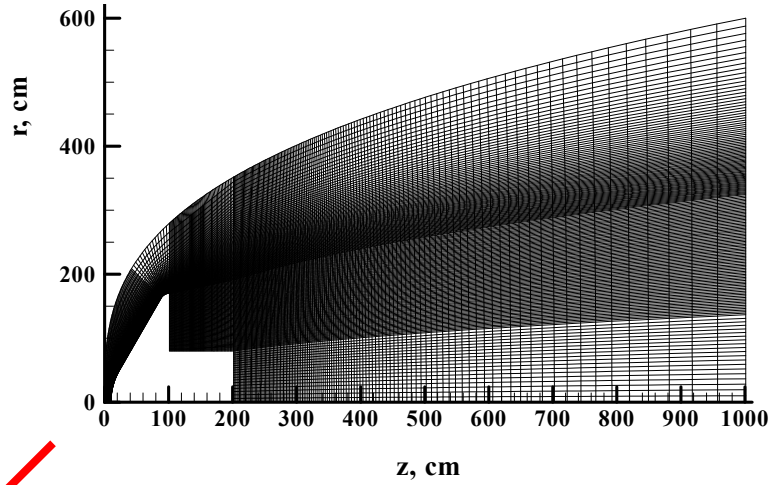
Multi-block/multi-grid technology

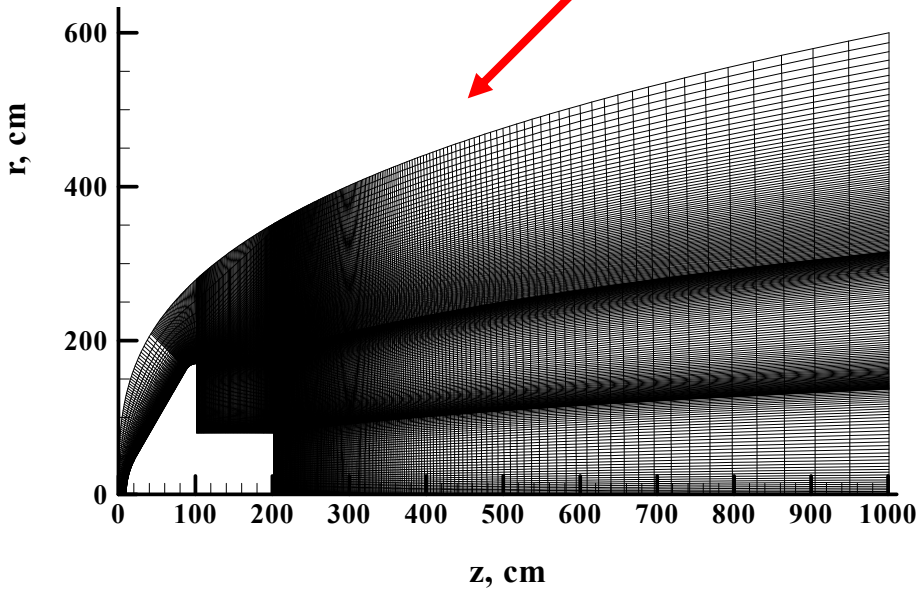


Initial grid

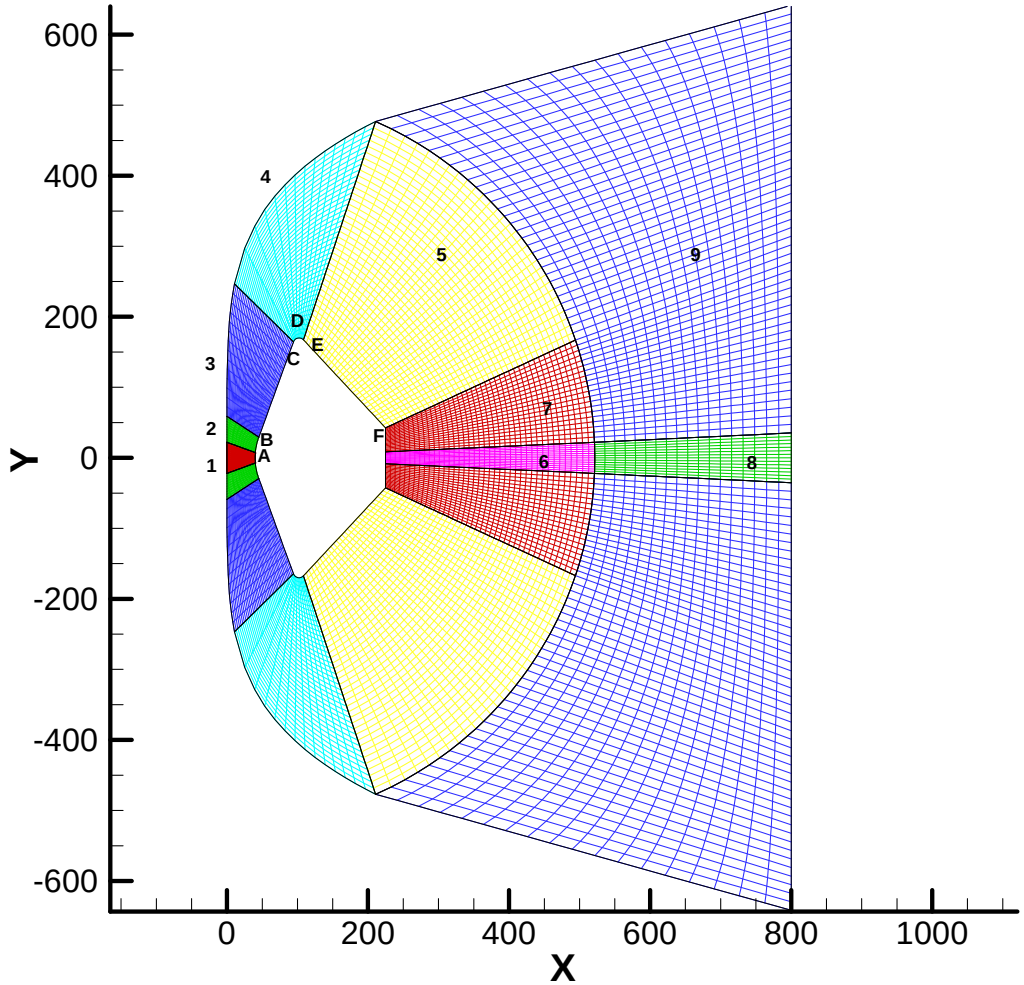


Intermediate grid

Final grid



Multi-Physics MHD/RadGD Numerical Simulation Models



3D-NERAT: Exomars

Multi-Physics MHD/RadGD Numerical Simulation Models

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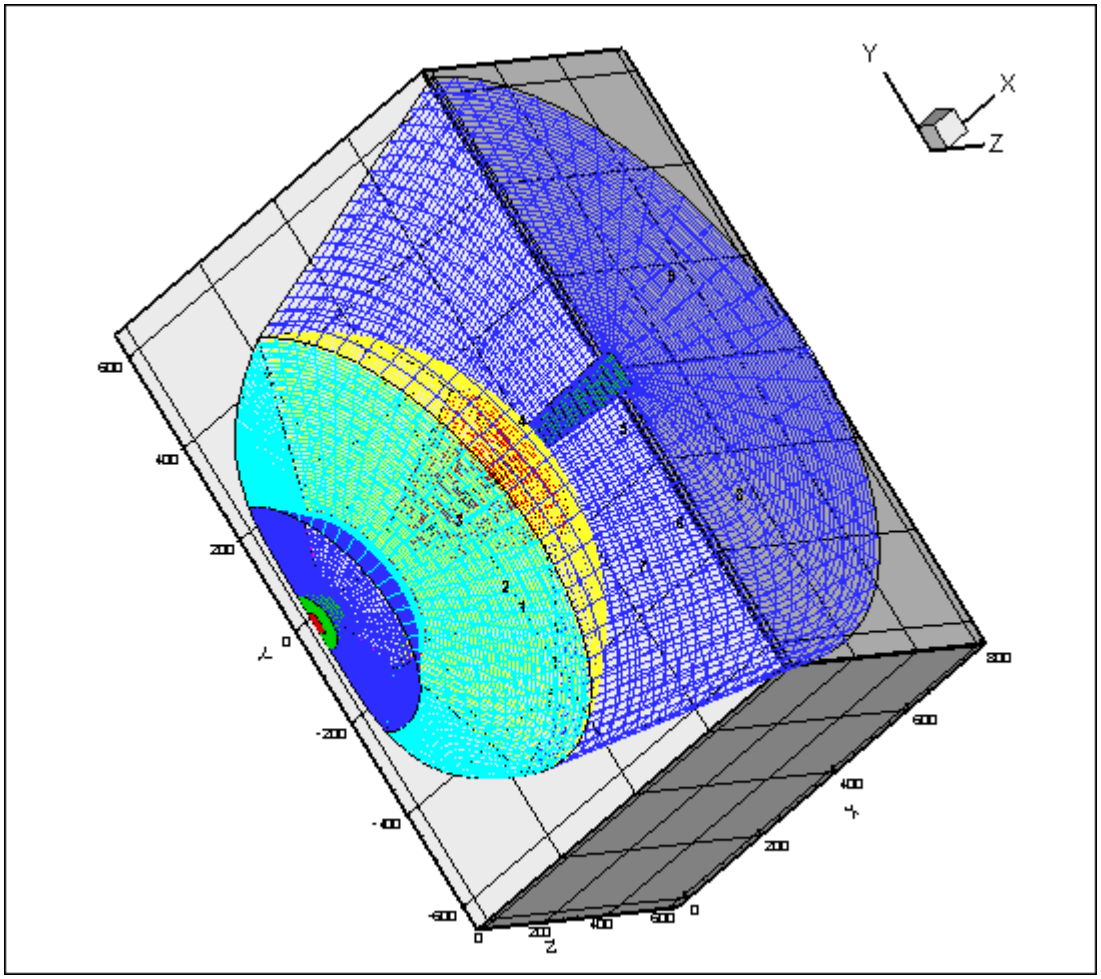
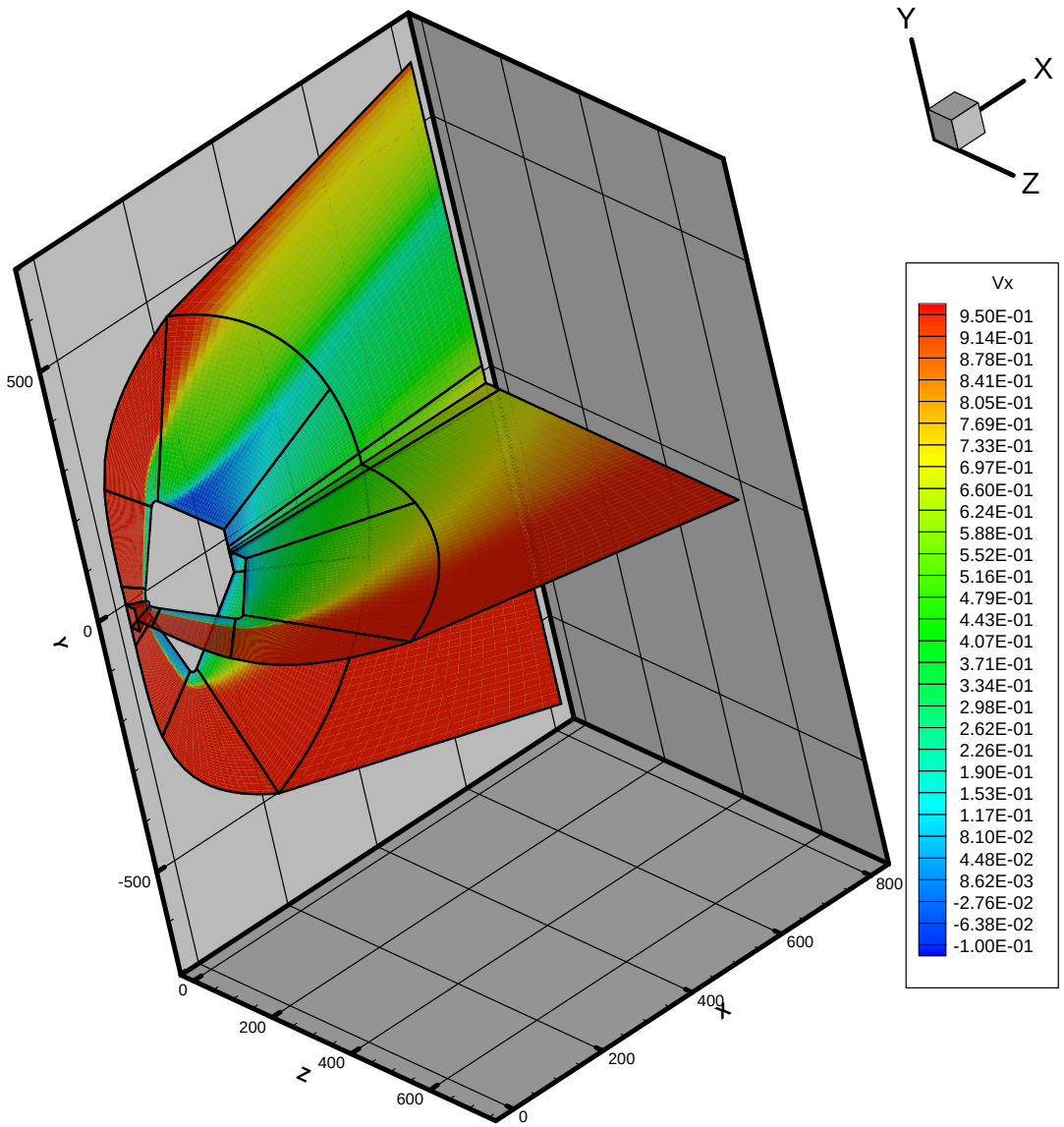


3D-NERAT: Exomars

Multi-Physics MHD/RadGD Numerical Simulation Models



3D-NERAT: Exomars

Multi-Physics MHD/RadGD Numerical Simulation Models

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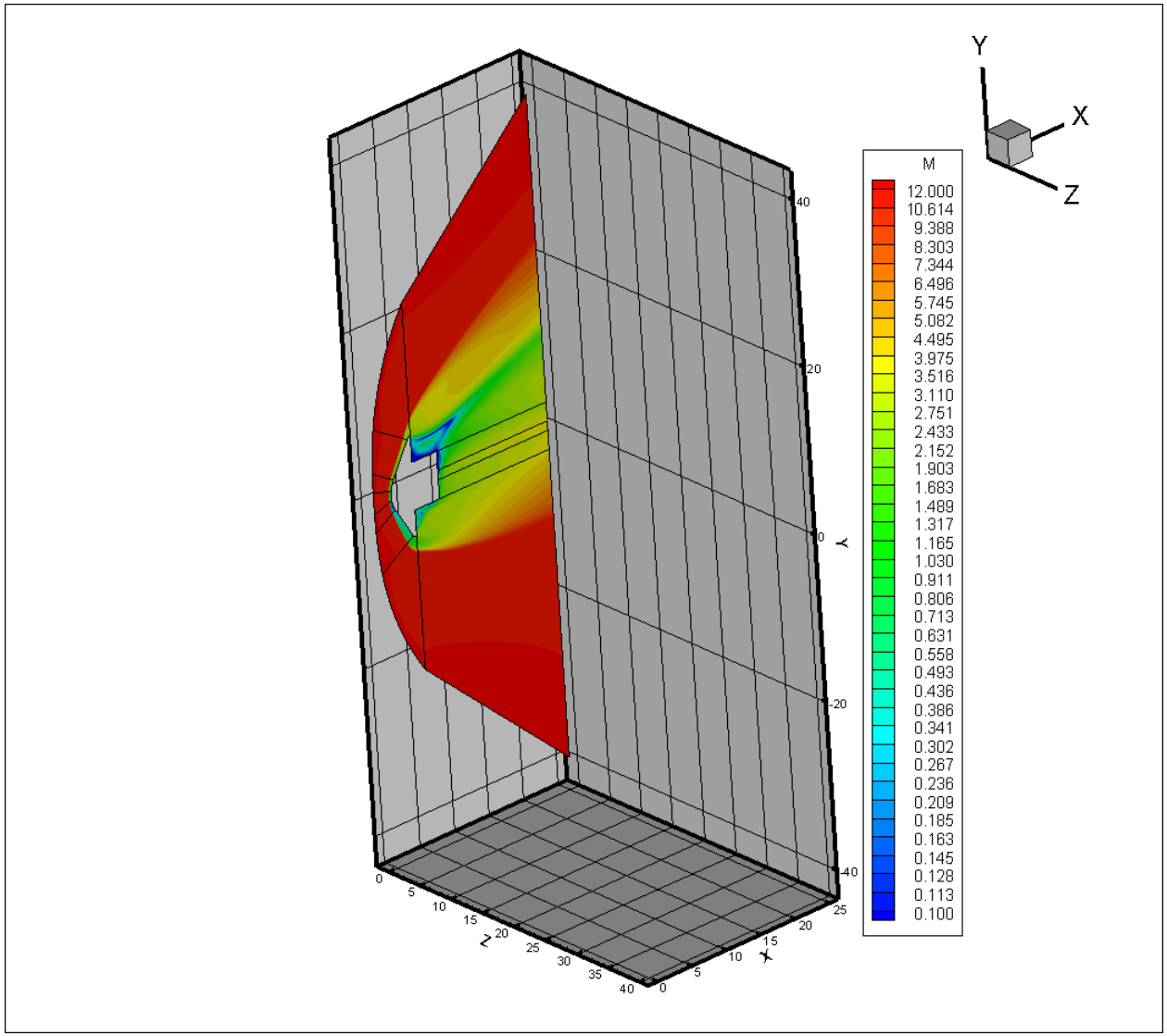

3D-NERAT: MSRO

RadGD/MHD multi-physics : On-going efforts

- Creation of radiative/kinetic models for description of non-equilibrium processes in hot gases and plasmas
- Creation of spectral optical models for LTE and non-LTE conditions
- Creation of 2D and 3D CFD/RadGD/RHT models for strong radiative-gasdynamic interaction (space vehicles, ground test facilities, laser/matter interaction, astrophysics, etc.)
- The use of the CFD/RadGD/RHT models for development of aerospace sciences
- CFD/RadGD/RHT models verification

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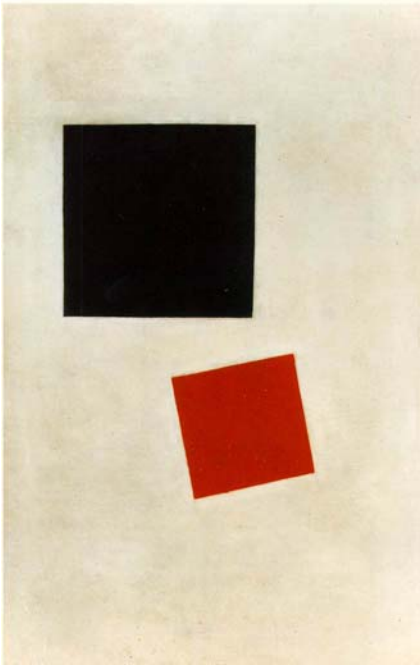
RadGD/MHD computational physics: On-going efforts

Kandinsky “Composition X” (1939)



Malevich Black Square and Red Square 1915

Acknowledgments

The author thanks the Organizing Committee for invitation to take part in ASTRONUM-2009

Multi-Physics Magnetohydrodynamics and Radiation Gas Dynamic Numerical Simulation Models for Aerospace Applications

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Radiative Gas Dynamics Laboratory