ISIMA

INTERNATIONAL SUMMER INSTITUTE FOR MODELING IN ASTROPHYSICS

Charge Exchange in the Colliding Winds of Hot Jupiters and Their Host Stars

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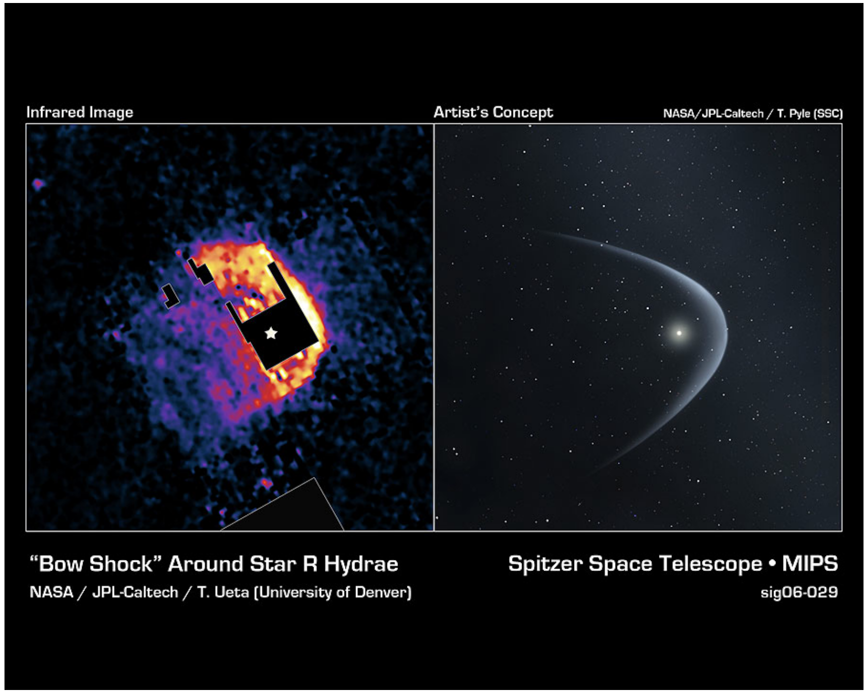
Example of colliding winds

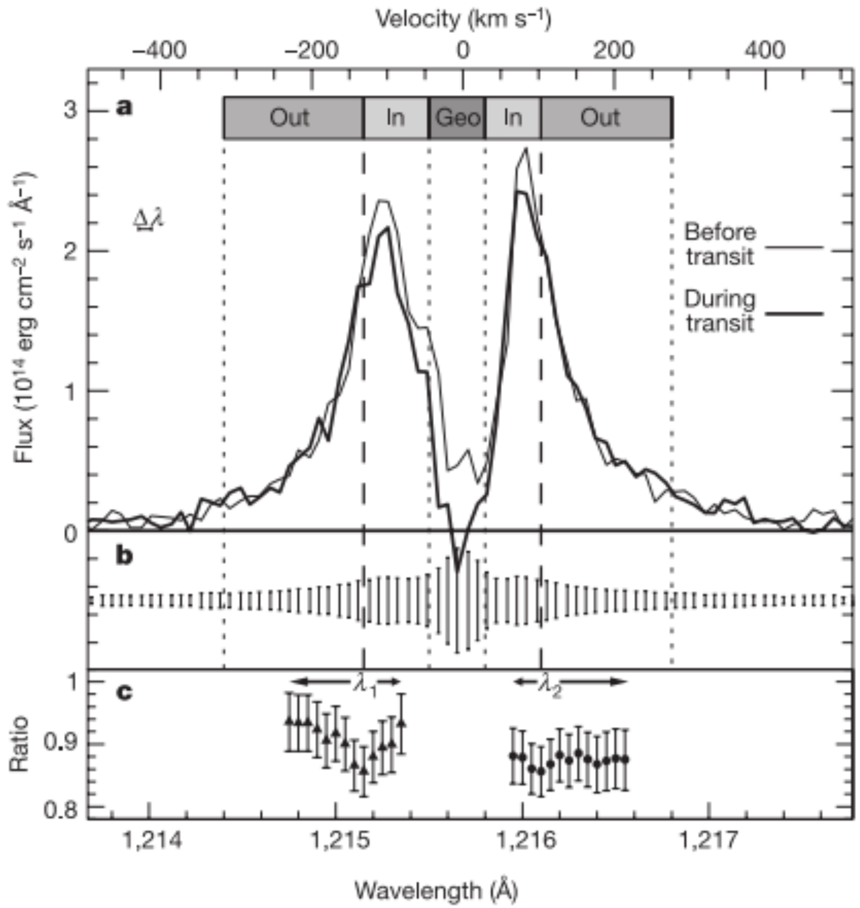
- Massive star winds in binaries
- Stellar wind on the atmospheric escape of an hot jupiter
- Stellar winds on the interstellar medium
- Solar wind on the Earth magnetosphere



- AGB Star R Hydrae in the far infrared

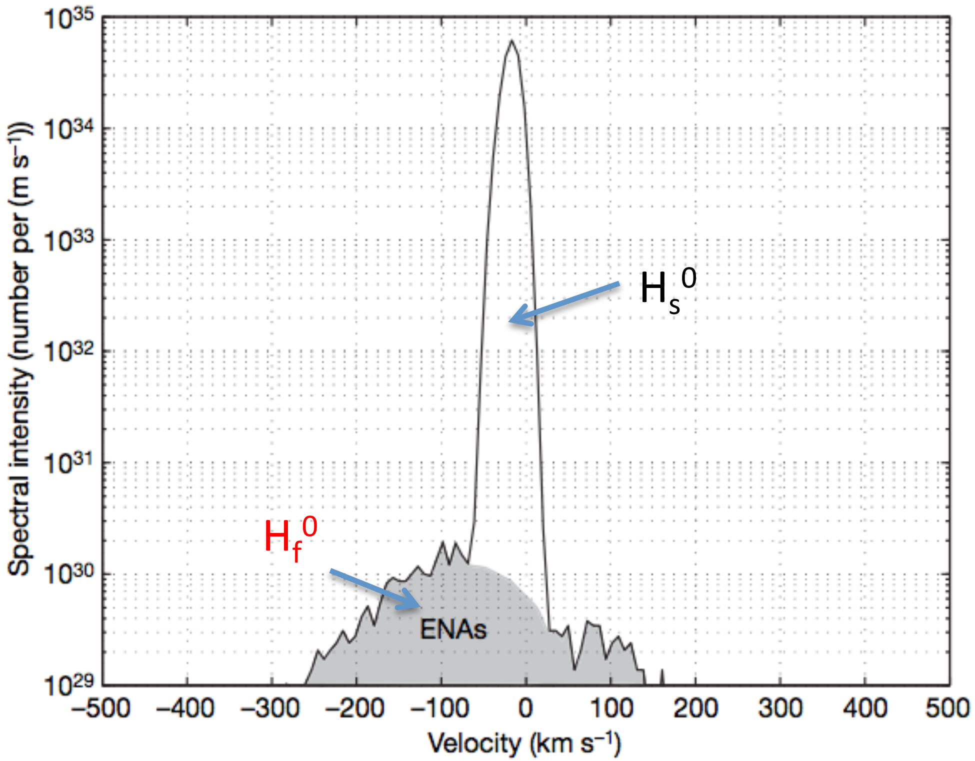
Ueta et al 2006

Atmospheric escape: HD209458b



- *Vidal-Madjar et al. 2003*
  - ~10% absorption of the stellar Lya spectrum
  - Absorption at high velocities (+/- 100 km/s)

Charge exchange: HD209458b



- *Holmström et al. 2008*
  - Charge exchange processes
  - $H_f^+ + H_s^0 \rightarrow H_s^+ + H_f^0$

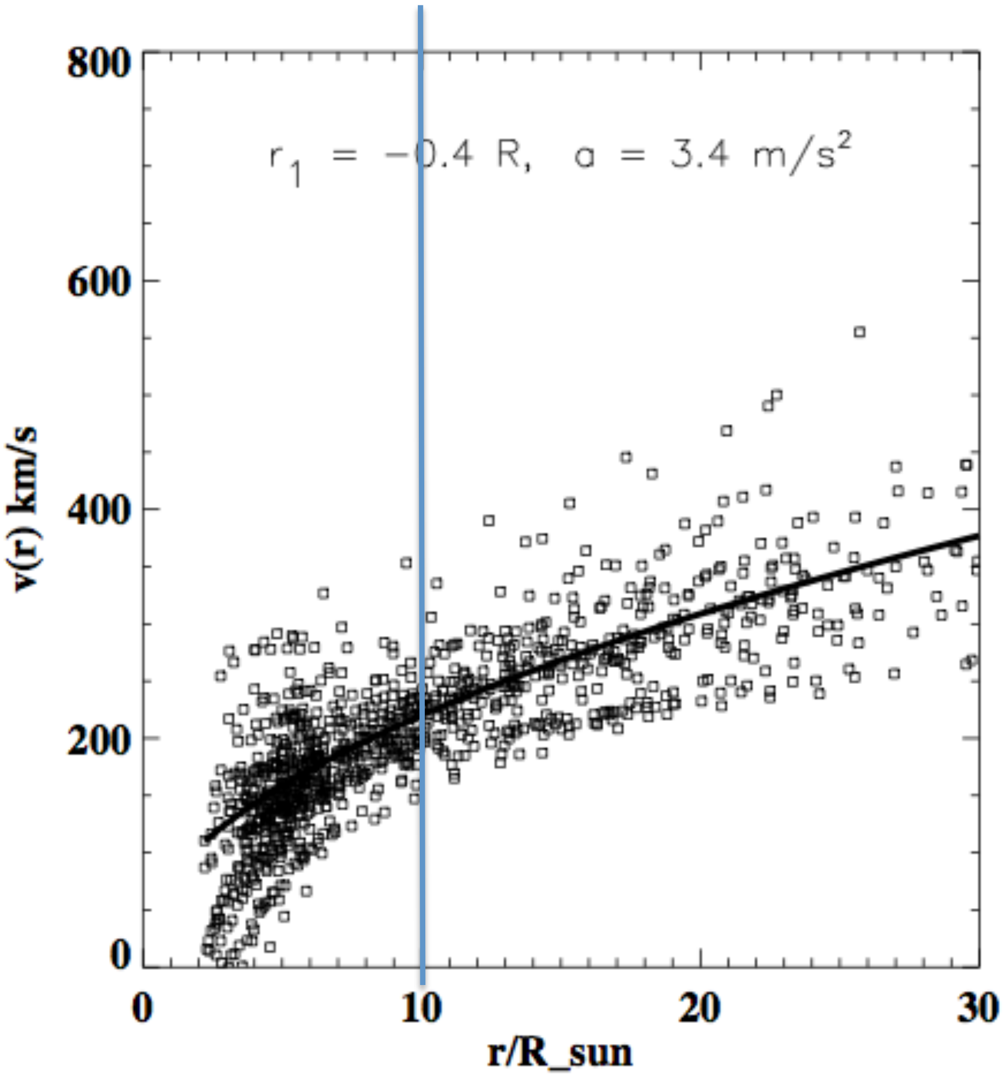
H_f^+: Fast ionized hydrogen in the solar wind

H_s^0: Slow neutral hydrogen in the planetary wind

H_f^0: Fast neutral hydrogen in the mixing layer

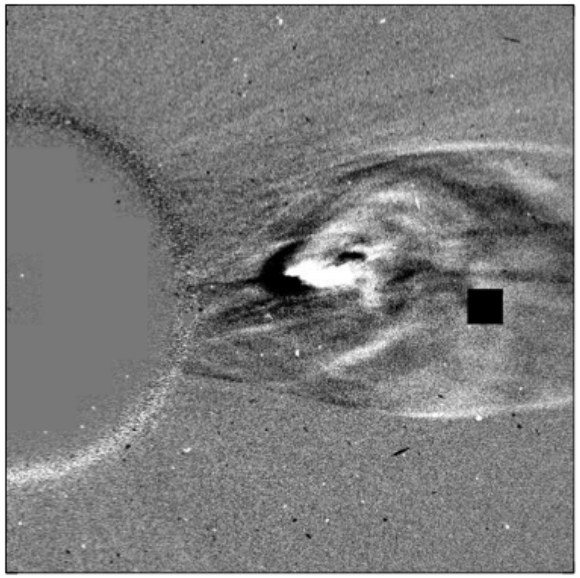
➢ But assume no shocks and a subsonic solar wind at 50 km/s

Solar wind: Data and Parker solution

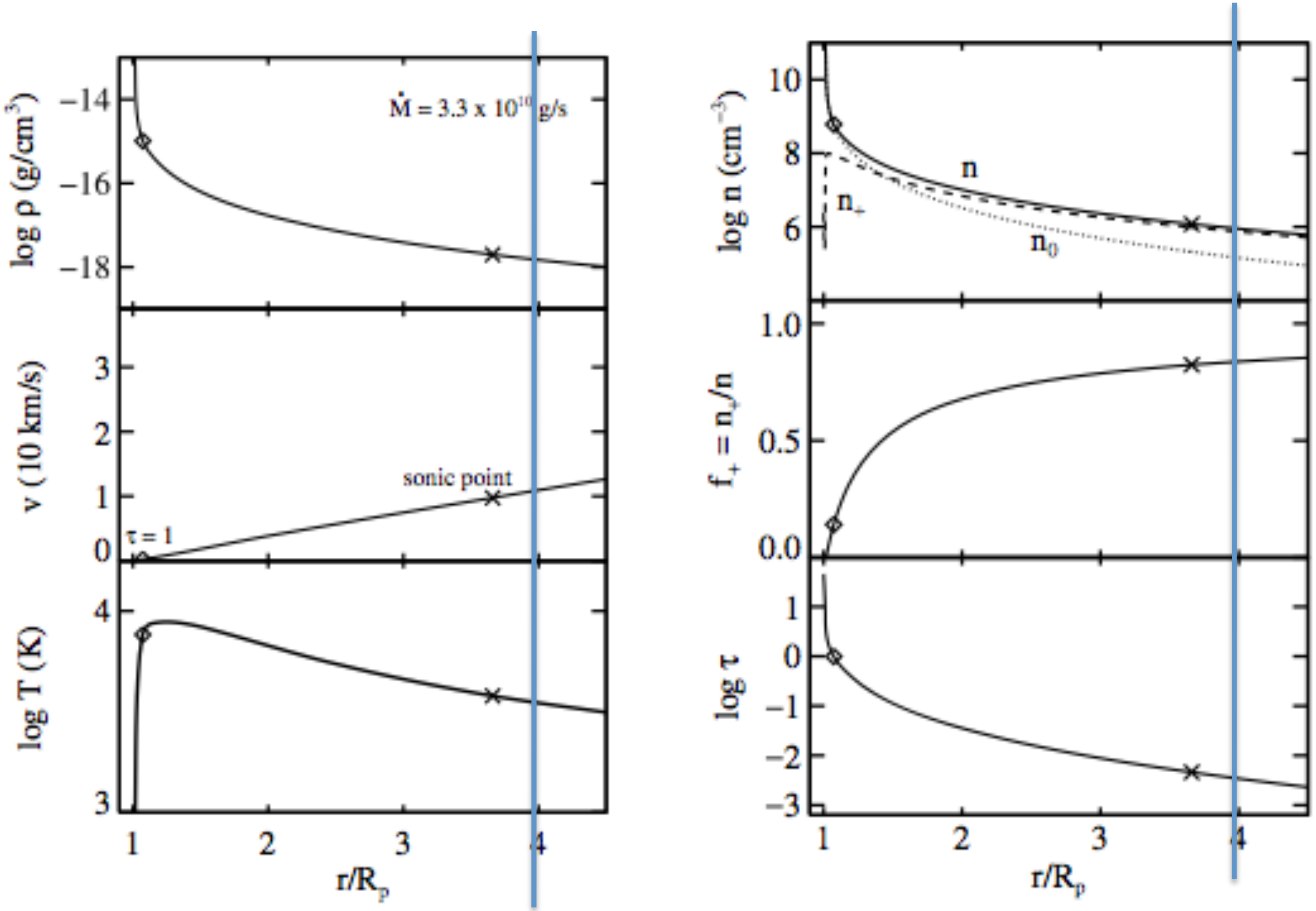


- *Sheeley et al 1997*
- At r = 10 R_* (0.05 au):

$$n_* = 2000/cm^3$$
$$T_* = 10^6 K$$
$$v_* = 250 km/s$$
$$f_*^+ = 1$$
$$c_* = 130 km/s$$
$$M_* \approx 2$$



Planetary wind model



At r = 4 R_p:

$$n_p = 10^6/cm^3$$
$$T_p = 7000K$$
$$v_p = 10km/s$$
$$f_p^+ = 0.8$$
$$c_p = 11km/s$$
$$M_p \approx 1$$

- *Murray-Clay et al. 2009*
  - Standard planetary wind model driven by the stellar UV flux

Cooling processes

Solar wind:

- Thermal conductivity (*Spitzer 1953*)
  - $K \approx 1.7 \times 10^4 (T/T_6)^{5/2} \quad [W/m/K]$
  - $D = K/\rho_* c \approx 4 \times 10^{21} \quad [cm^2/s]$
  - $t_{cool} \approx R_p^2/D \approx 2 \times 10^{-2} s$
- Hydrodynamic timescale:

$$t_{hd} \approx R_*/v_* \approx 4 \times 10^4 s$$

➡ $t_{cool} << t_{hd}$

➢ Isothermal solar wind at T= 10^6 K

Planetary wind:

- Lya cooling rate at 7000 K

$$\Lambda \approx 2 \times 10^{-18} cm^3 erg/s$$

$$t_{cool} \approx e_p/(n_p^2 \Lambda) \approx 20s$$

- Hydrodynamic timescale:

$$t_{hd} \approx R_*/v_p \approx 4 \times 10^5 s$$

➡ $t_{cool} << t_{hd}$

➢ Isothermal planetary wind at T= 7000 K

➢ Simulations with $\gamma = 1.01$

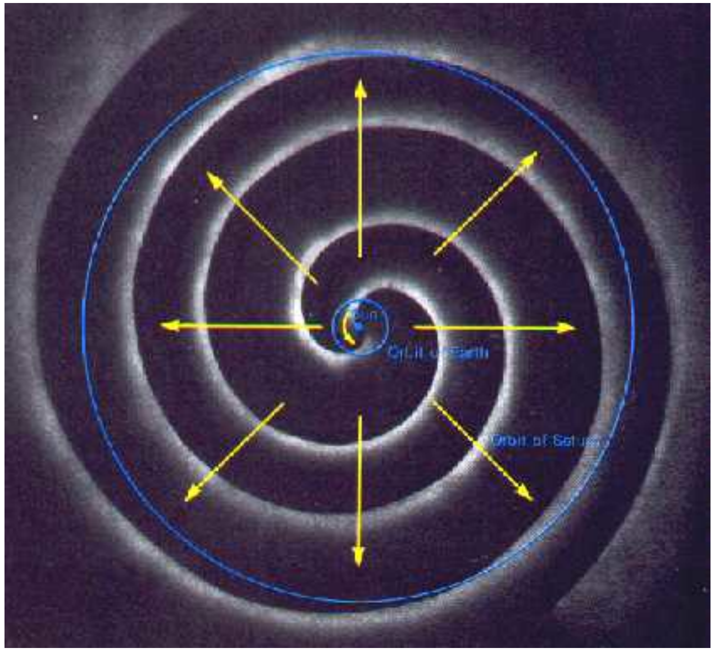
Neglected effects

- Magnetic field *Weber & Davis 1967*

At r = 0.05 au (10 R_*):

$$B_r \approx 0.1G \qquad B_\phi \approx 4 \times 10^{-4}G$$

$$\beta_\phi \approx 157$$



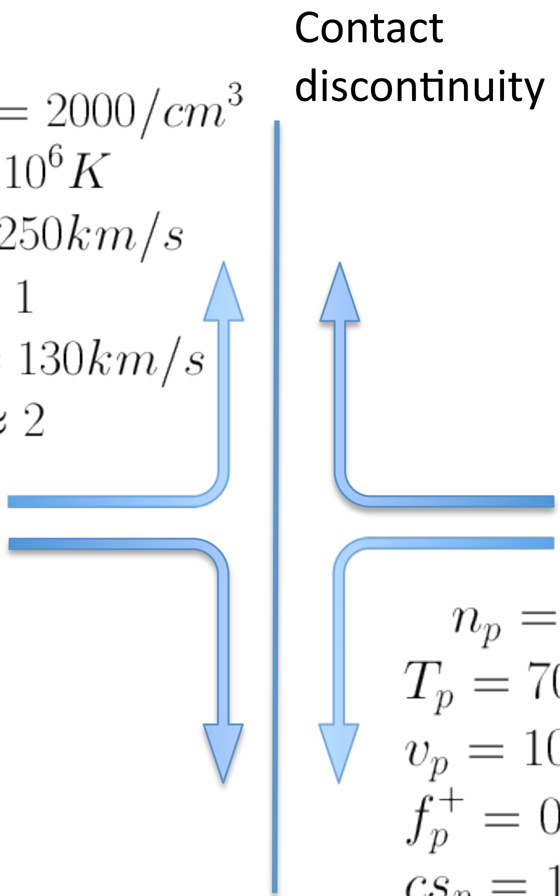
- Coriolis force

$$a \approx 2\Omega v_p \qquad \Delta v \approx 2\Omega R_*$$

➢ $\Delta v \approx 20km/s$

- 3D simulations
- 2D simulations
- Semi-analytic solution for bow shocks
- Plan-parallel order of magnitude estimation

Order of magnitude estimation



$n_s = 2000/cm^3$
$T_s = 10^6 K$
$v_s = 250km/s$
$f_s^+ = 1$
$cs_s = 130km/s$
$M_s \approx 2$

$n_p = 10^6/cm^3$
$T_p = 7000K$
$v_p = 10km/s$
$f_p^+ = 0.8$
$cs_p = 11km/s$
$M_p \approx 1$

- Mixing by Kelvin Helmholtz instabilities

$$v_{mix}, \quad t_{mix}, \quad l_{mix}$$

- Charge exchange cross section:

$$\sigma_{ce} \approx 2 \times 10^{-15} cm^2$$

- Lya opacity at line centre:

$$\tau \approx 3.31 \times 10^{-14} T_4^{-0.5} N_{H^0}$$

- Estimations:

$$N_{H_f^0} \approx 10^{15}/cm^2$$

$$\tau \approx 3$$

2D structure of the interface

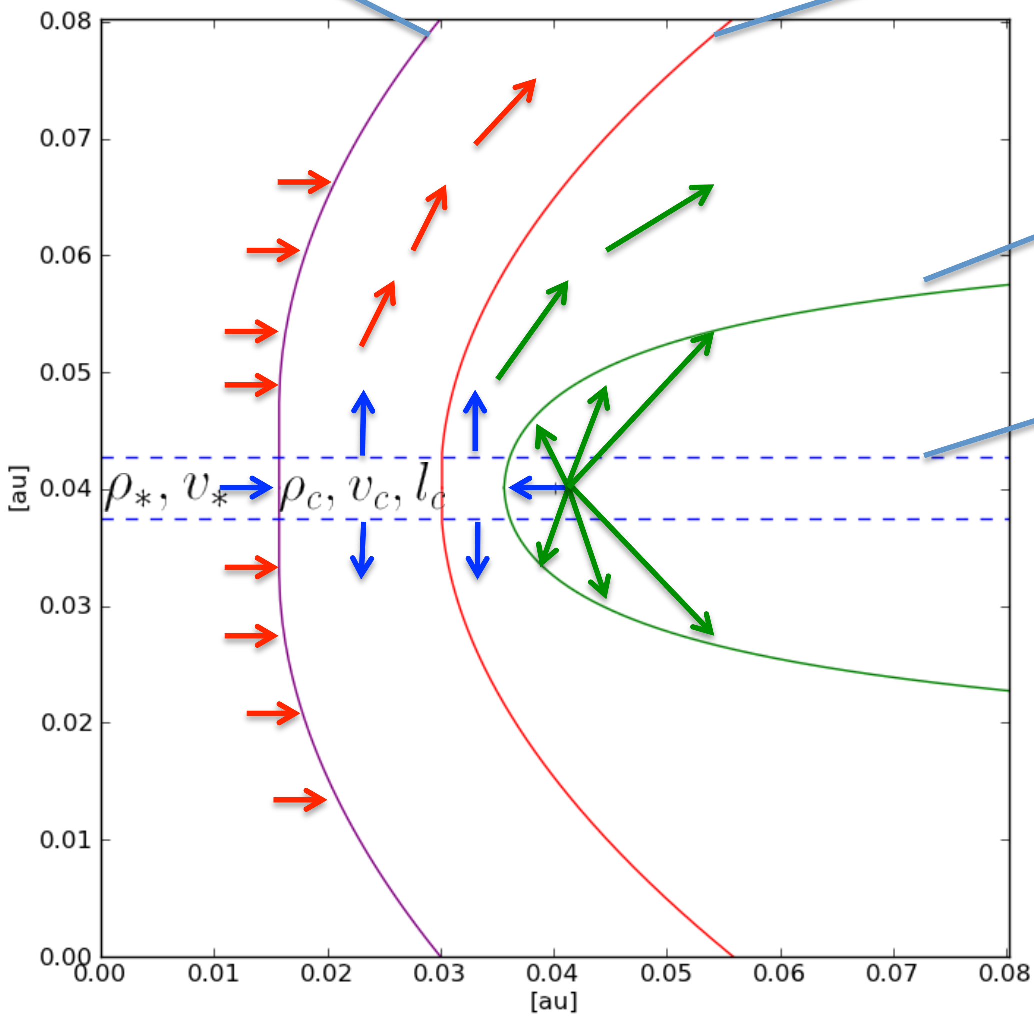
Outer shock

Contact discontinuity

Inner shock,
perpendicular
momentum balance
Stevens et al 1992

4 R_p: plane
parallel limit

$$\rho_c = \rho_* M_*^2$$
$$v_c \approx c_*$$
$$l_c \approx 4R_p/M_*$$

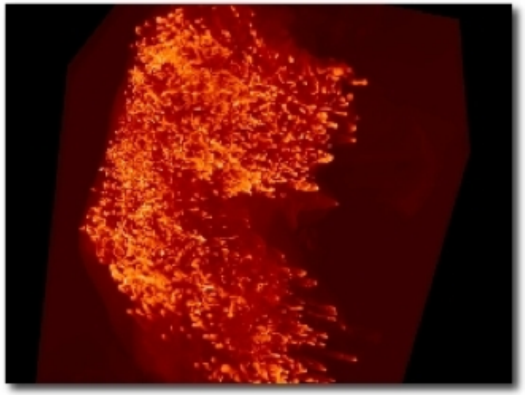


2D/3D simulations, HERACLES

HERACLES

3D parallel code for hydrodynamics, MHD, radiative transfer and gravity

Home | Features | Test suite | Gallery | Documentation | Publications | Contact



HERACLES is a 3D hydrodynamical code used to simulate astrophysical fluid flows. It uses a finite volume method on fixed grids to solve the equations of hydrodynamics, MHD, radiative transfer and gravity. This software is developed at the Service d'Astrophysique, CEA/Saclay as part of the COAST project and is registered under the CeCILL license.

The code is developed by:
- Code architecture: Edouard Audit
- Parallelization: Edouard Audit
- Hydrodynamics: Edouard Audit
- Radiative transfer: Matthias González, Edouard Audit & Neil Vaytet
- MHD: Sebastien Fromang, Patrick Hennebelle & Romain Teyssier
- Gravity: Pascal Tremblin
- HDF5 output: Bruno Thooris
- Website: Neil Vaytet

HERACLES simulates **astrophysical fluid flows** using a grid based Eulerian finite volume Godunov method. It is capable of simulating **pure hydrodynamical** flows, **magneto-hydrodynamic** flows, **radiation hydrodynamic** flows (using either flux limited diffusion or the M1 moment method), **self-gravitating** flows using a Poisson solver or all of the above. HERACLES uses cartesian, spherical and cylindrical grids. Current ongoing developments include a **multi-grid** method and a **multi-group** scheme for the radiative transfer.

The full package can be downloaded here: heracles.tar.gz
Current version: 2.0 (20 September 2010)
Version history

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COAST project home page - Service d'Astrophysique, CEA/SAp

2D/3D simulations, Charge exchange

- Passive scalars advected to the flow

$$\frac{\partial x_f^+ \rho}{\partial t} + \nabla \cdot (u x_f^+ \rho) = 0$$

$x_f^+ = 1$ in solar wind

$$\frac{\partial x_s^0 \rho}{\partial t} + \nabla \cdot (u x_s^0 \rho) = 0$$

$x_s^0 = 0.2$ in planetary wind

- Charge exchange process $H_f^+ + H_s^0 \rightarrow H_s^+ + H_f^0$

$$dx_f^+ n_H / dt = -\sigma_{ce} x_f^+ x_s^0 n_H^2 v_{th}$$

$$dx_s^0 n_H / dt = -\sigma_{ce} x_f^+ x_s^0 n_H^2 v_{th}$$

$$dx_f^0 n_H / dt = \sigma_{ce} x_f^+ x_s^0 n_H^2 v_{th}$$

2D simulation, post processing Lya spectra

- Opacity for Lya line:

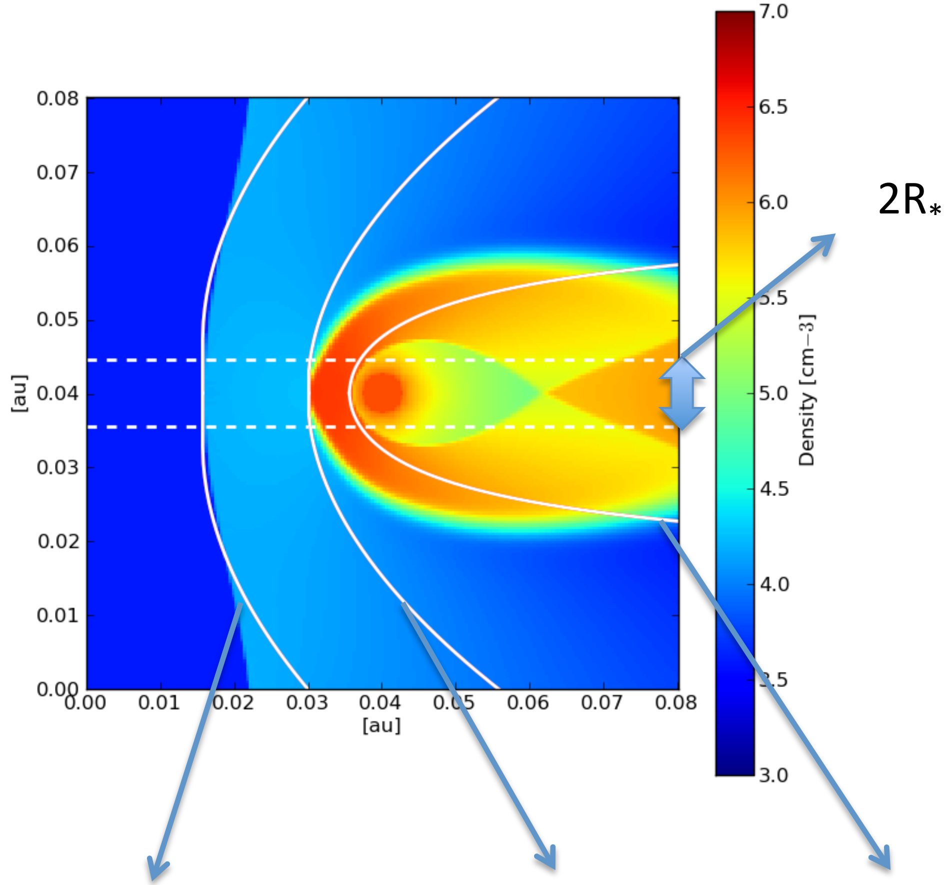
$$\tau_\nu = 1.041 \times 10^{-14} T_4^{-0.5} N_H e^{-(\nu-\nu_0)^2/\Delta\nu_{th}^2}$$

- Doppler shift: $\nu_0 = (1 + v/c)\nu_{Lya}$

- Thermal broadening: $\Delta\nu_{th} = \nu_{Ly\alpha}\sqrt{2k_b T/m_H}/c$

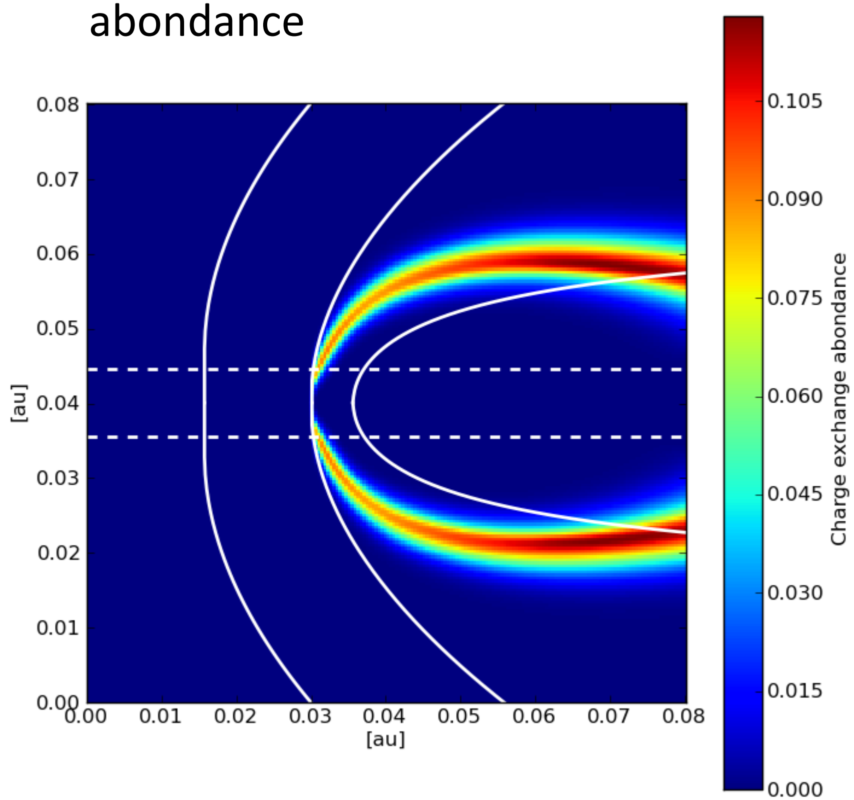
Results

200x200 2D cartesian t=1.2^{E}6 s



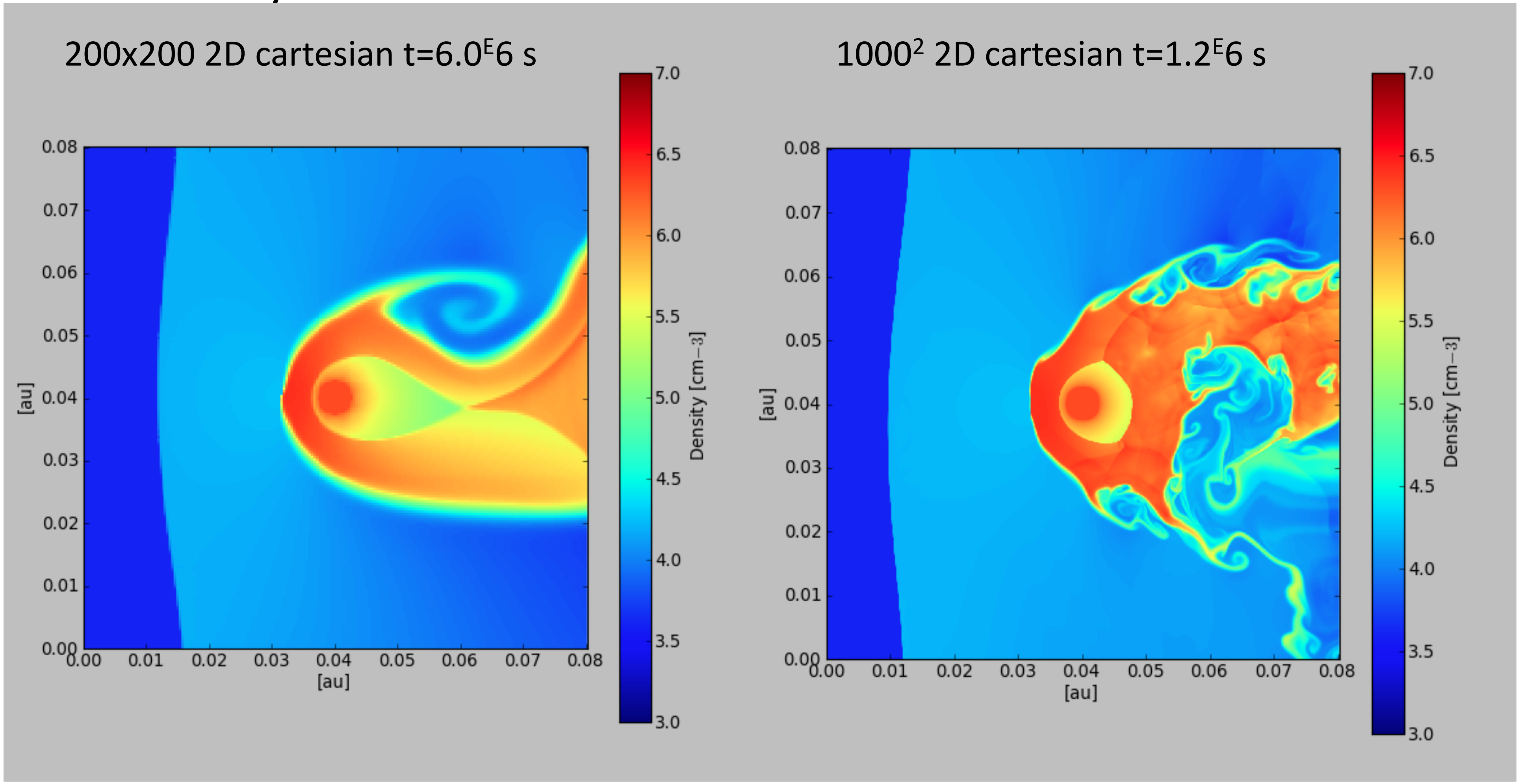
Outer shock   contact discontinuity   inner shock

Fast Neutral hydrogen abondance



Results

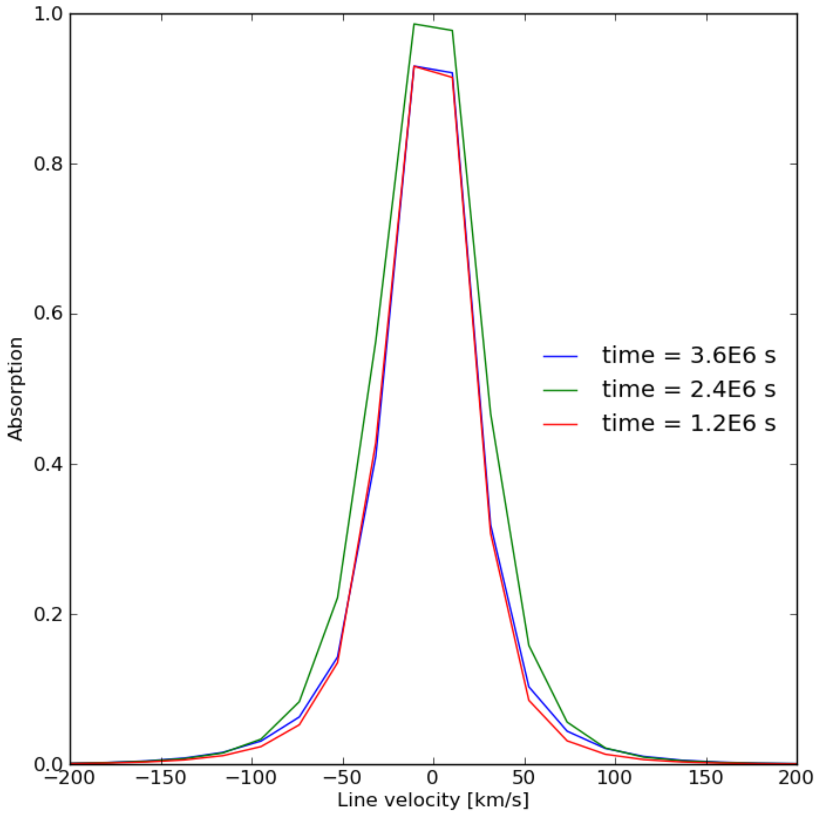
- Steady state ?

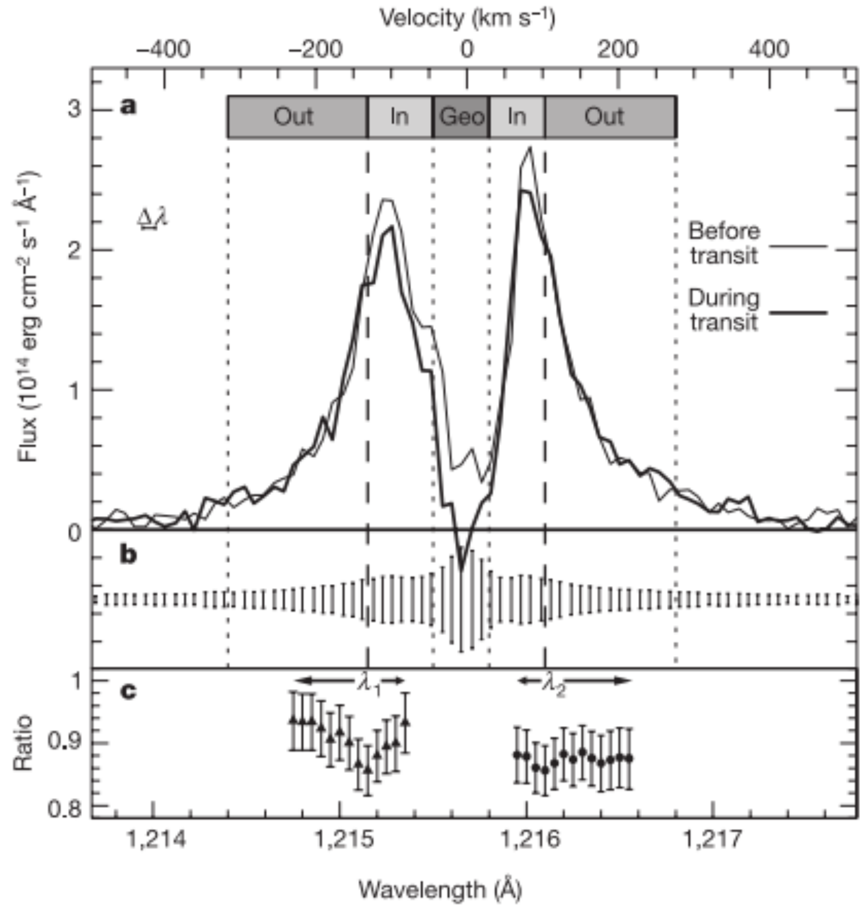


Results

- Absorption spectra

200x200 at different time

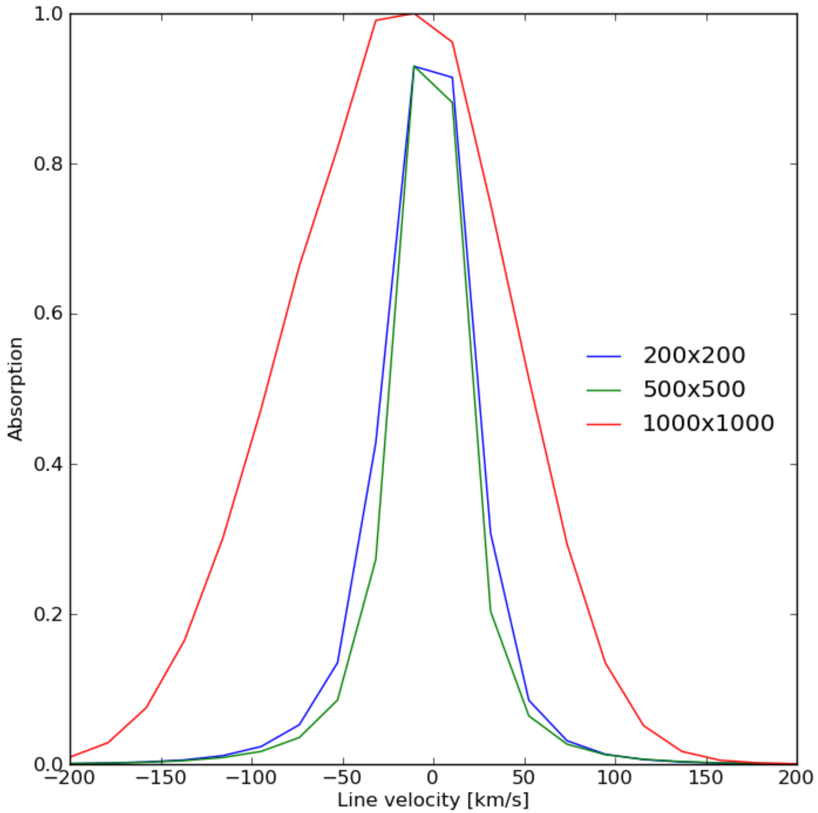


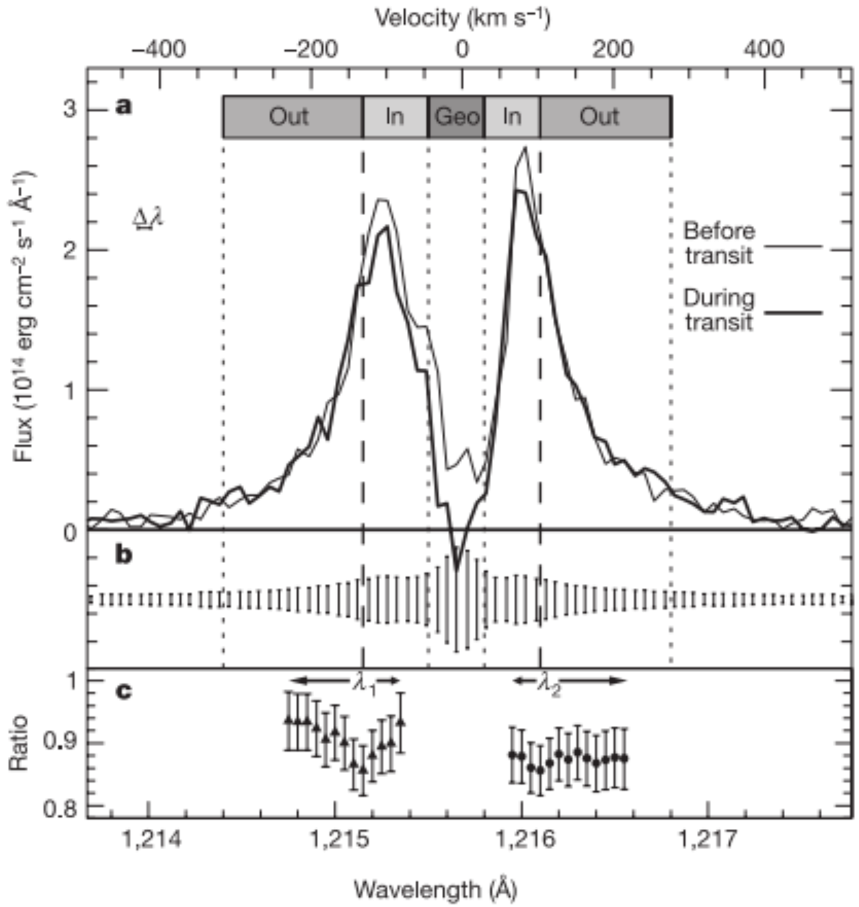


Results

- Absorption spectra

Different resolutions at t=1.2^{E}6 s





Conclusion

- We obtained Lya absorption spectra due to charge exchange processes in 2D HD simulations

- Upcoming : magnetic field, 3D