

# Some Pending Questions in Laboratory HED Astrophysics

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**High Energy Density plasmas created with long (> 1 ns) pulse duration at least three opportunities. Lasers offers**

The study of the **microscopic properties** of plasmas in a large range of temperature and density, relevant for astrophysical objects:

Equation of state for planet interiors  
Opacities for stellar interiors  
Reaction *rates* in various astrophysical plasmas

The study of the **dynamical properties** of plasmas at large velocities, actually observed in various astronomical phenomena..

Radiative shocks  
Accretion/ejection phenomena  
SNe explosions  
Jets and their interactions with ambient medium  
Hydro Instabilities

**Benchmarking** of astrophysical codes by experiments, numerical simulations.

Needs to use the *same* code for the interpretation and modelization of astrophysical objects. In some restricted cases, possibility of a scaling laboratory astronomical object.

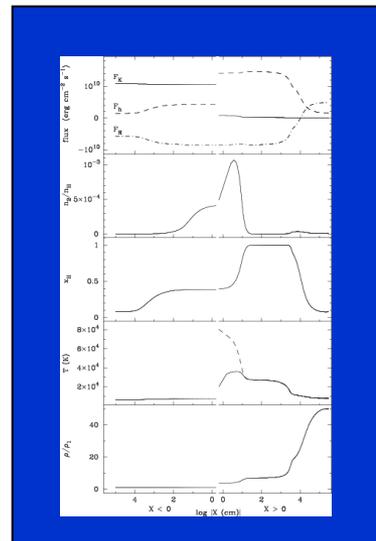
# Radiative Shocks and Ionization Waves

## Physics of radiative shocks has applications to

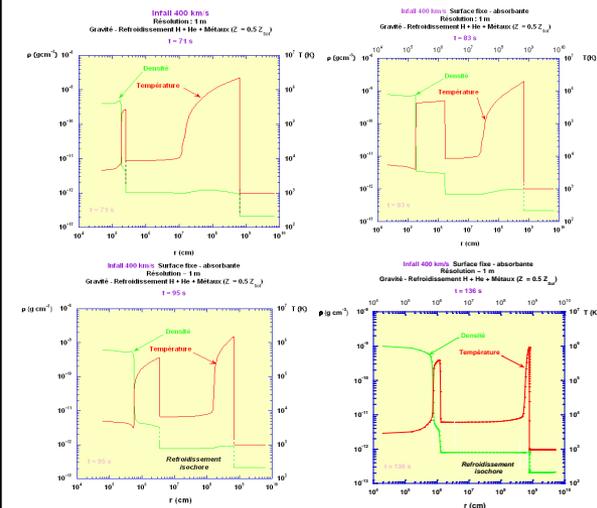
- shock waves in young or old accreting stars,
- shock waves in pulsating atmospheres of evolved stars,
- re-entry shocks,
- shocks in the context of Inertial Confinement Fusion
- ...



Kepler - Chandra

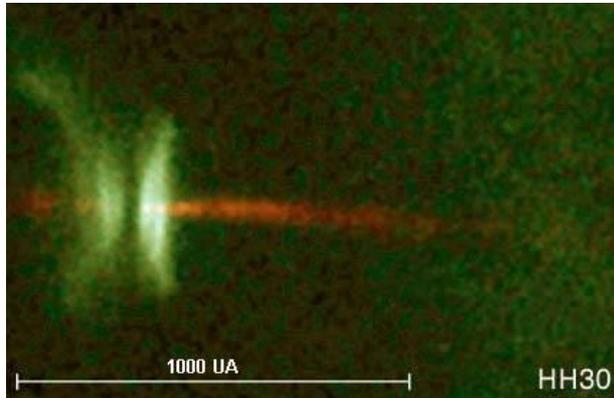


Pulsation W Vir, RV Tau, Mira ...



Pulsating accretion shocks on stars

**Accretion** is the most efficient mechanism to release energy in universe  
Accompanied by violent hydrodynamic **ejection** phenomena such as collimated jets and strong radiative shocks  
They are characteristic features of **star-forming regions**, or accreting galactic black holes.



Accretion shocks luminosity **gives an estimate of the accretion rate**.  
These flows are very complex structures → crude modeling approximations

Shocks from Accretion & Ejection impact upon

- The evolution of the stars,
- The evolution of the surrounding disk,
- Energy injection and turbulence in the Interstellar medium.

Mastering the physics of Shocks & Instabilities →  
Observations / Experiments / Numerical Modelization

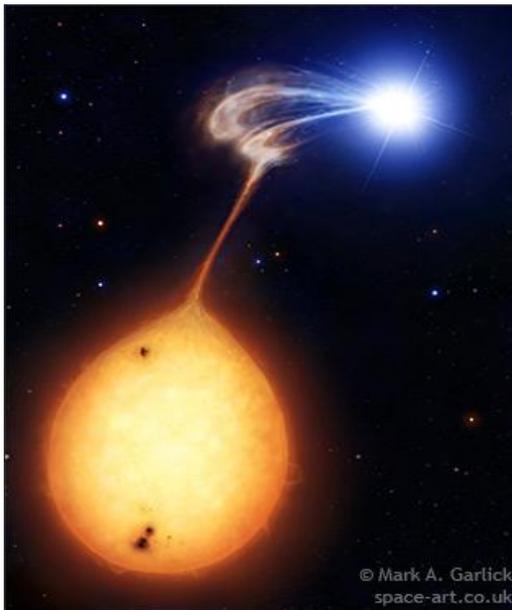
# Accretion Shocks : Two Main Regimes

Accretion in old binary systems :  
«red giants» → «white dwarfs» → SNIa

$\tau < 1$  : formation of radiative shocks  
« on the spot » cooling

Accretion in young star-disk systems : A  
clue to the accretion rate

$\tau > 1$  : formation of radiative shocks with  
ionization waves precursors



Easy scaling  
laboratory vs. astrophysical object

- Characterization of the shocked plasma :  $T, \rho$
- Structure
- Stability (vs.  $\Lambda, \dots$ )

↑  
Movie

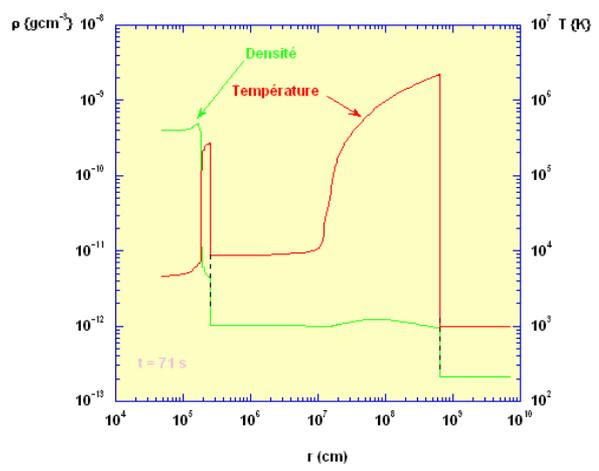


Star formation in  
Carina Nebula (HST)

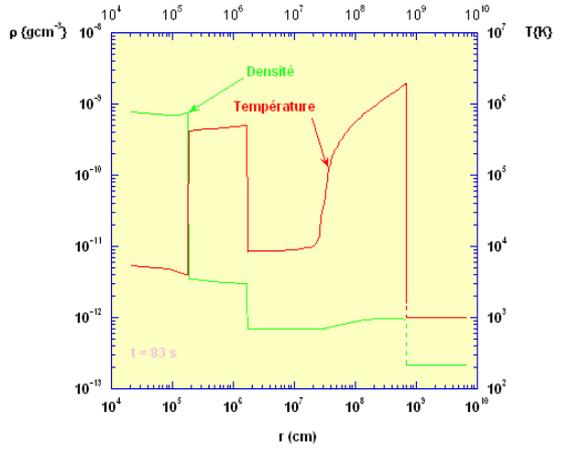
1. **Structuring** matter by **radiation** and **instabilities**
2. **Atomic Physics** : charge states distribution, edge shifts ... affect the structure of the radiative waves

# Cooling Accretion Shocks May Develop a Complex, Time Dependent Structure

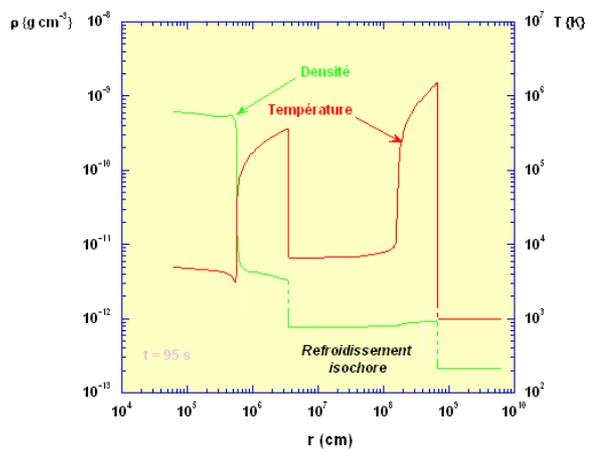
**Infall 400 km/s**  
 Résolution : 1 m  
 Gravité - Refroidissement H + He + Métaux ( $Z = 0.5 Z_{\text{sol}}$ )  
 t = 71 s



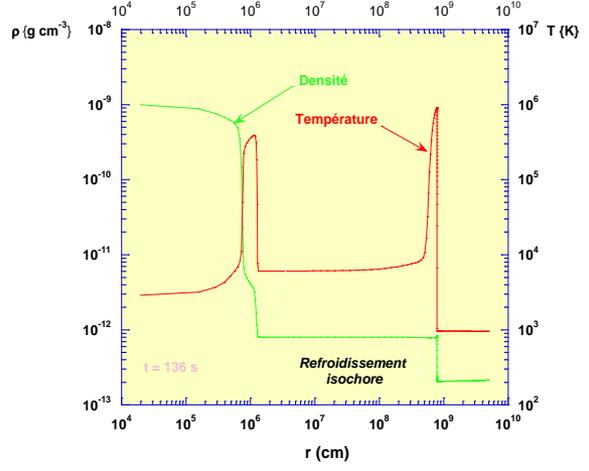
**Infall 400 km/s Surface fixe - absorbante**  
 Résolution : 1 m  
 Gravité - Refroidissement H + He + Métaux ( $Z = 0.5 Z_{\text{sol}}$ )  
 t = 83 s



**Infall 400 km/s Surface fixe - absorbante**  
 Résolution : 1 m  
 Gravité - Refroidissement H + He + Métaux ( $Z = 0.5 Z_{\text{sol}}$ )  
 t = 95 s



**Infall 400 km/s Surface fixe - absorbante**  
 Résolution : 1 m  
 Gravité - Refroidissement H + He + Métaux ( $Z = 0.5 Z_{\text{sol}}$ )  
 t = 136 s



**Rapid cooling quasi isochoric.**

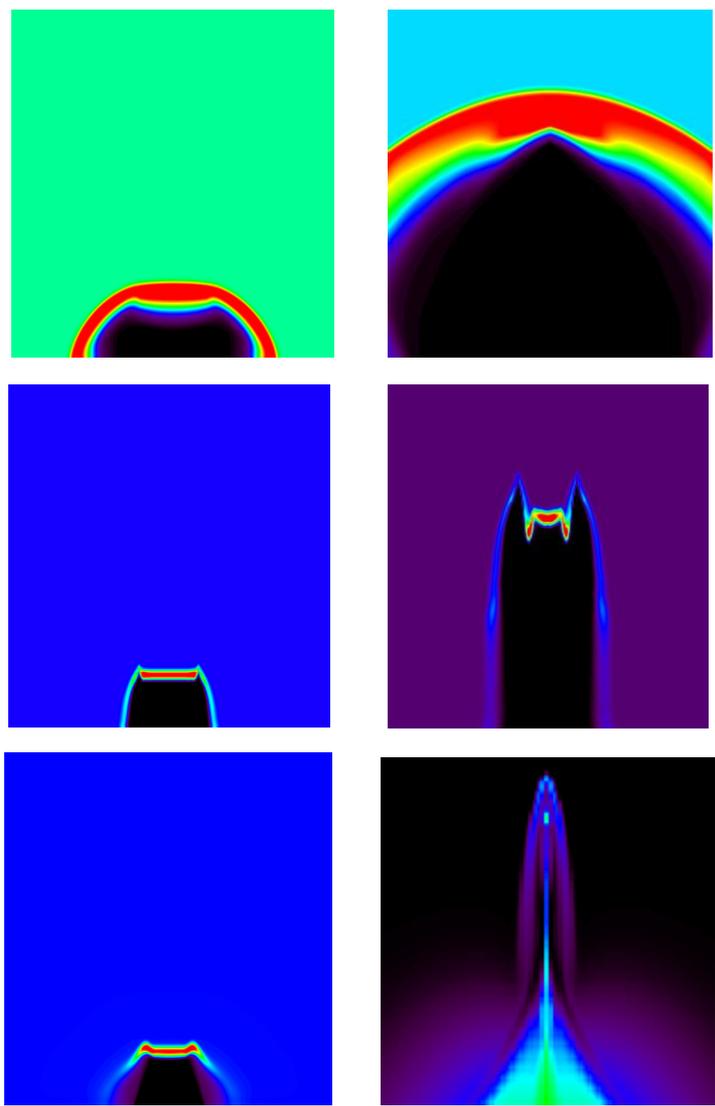
**Drives a pressure gradient, launching a second shock onto the chromosphere of the accreting star**

# Matter Structured by Radiation

## Illustrating Optically Thin or Thick Radiative Transfer

irfu  
institut de  
cea  
recherche sur les lois  
fondamentales de  
l'univers  
saclay

Code HERACLES (CEA/Sap)



500 years

2 000 years

Pure hydrodynamics

Hydrodynamics  
+  
cooling “on the spot”

Hydrodynamics  
+  
radiative transfer

# Radiative Shocks and Jets : some issues

Measurements of **the thickness** and **temperature structure** of ( planar, spherical) **radiative shock** : Laser ablated solid foil → ionization wave in a foam, radiative shock in gas Ar, Kr, Xe, mixture ...  
Shock velocity :  $D \sim 100 \text{ km s}^{-1}$       Transverse scale :  $l = 1\text{-}2 \text{ mm}$

Creating **jets with increasing emissivity** in media of various optical (*cooling vs. transfer*).

Study of the **slow-down, deflexion** and **interaction** of **jets**  
Jets may be produced by interaction of « pusher » impacting a shield with one or two holes in it.

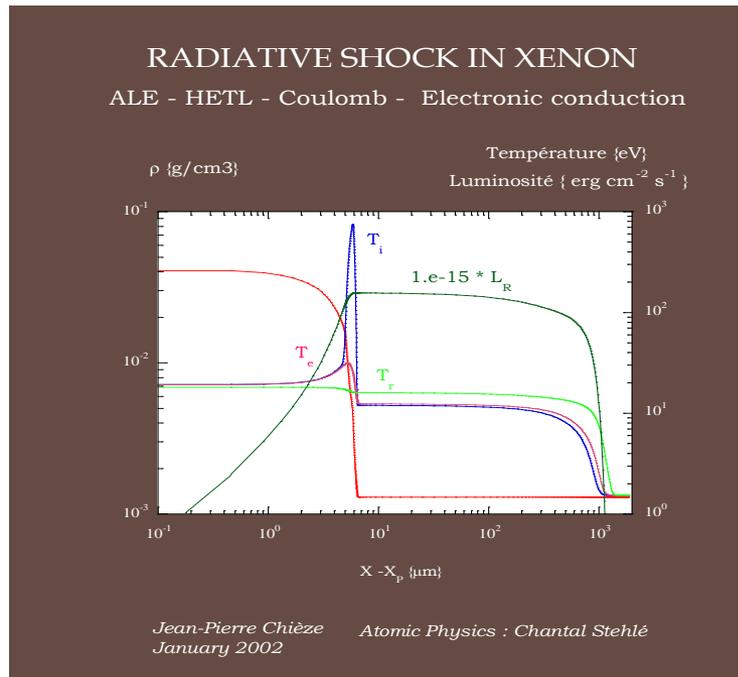
Creating **turbulents jets** (possibly radiative). Characterization of turbulence for comparaisn with different prescriptions to describe turbulence. Rôle of transfer/cooling on turbulence.

Impact of a jet with a **clumpy, denser medium**.

# Diagnostics : General Needs

- **Absorption spectroscopy** in the shock :  
resolution  $\lambda/\delta\lambda \sim 300$  or better.  
Use a **backlighter** to sample the dense parts of shocks.

- Need for a « **flat top** » intensity **spatial profile**  
over large sections.



- **Thomson scattering**  
(X-ray, UV)

Measurement of  $T_e$ ,  $T_i$ ,  $n_e$   
in shocks, jets and  
complex flows, ...

Measurement **over long durations** : about 50 ns needed (present experiments 50 km/s, 0.1 bars , Xe)

## Spectro Imaging

Snapshots in various spectral windows (visible, XUV and X), using tracers.

## Visar

Measure of the instantaneous velocity of interfaces.

## Interferometry

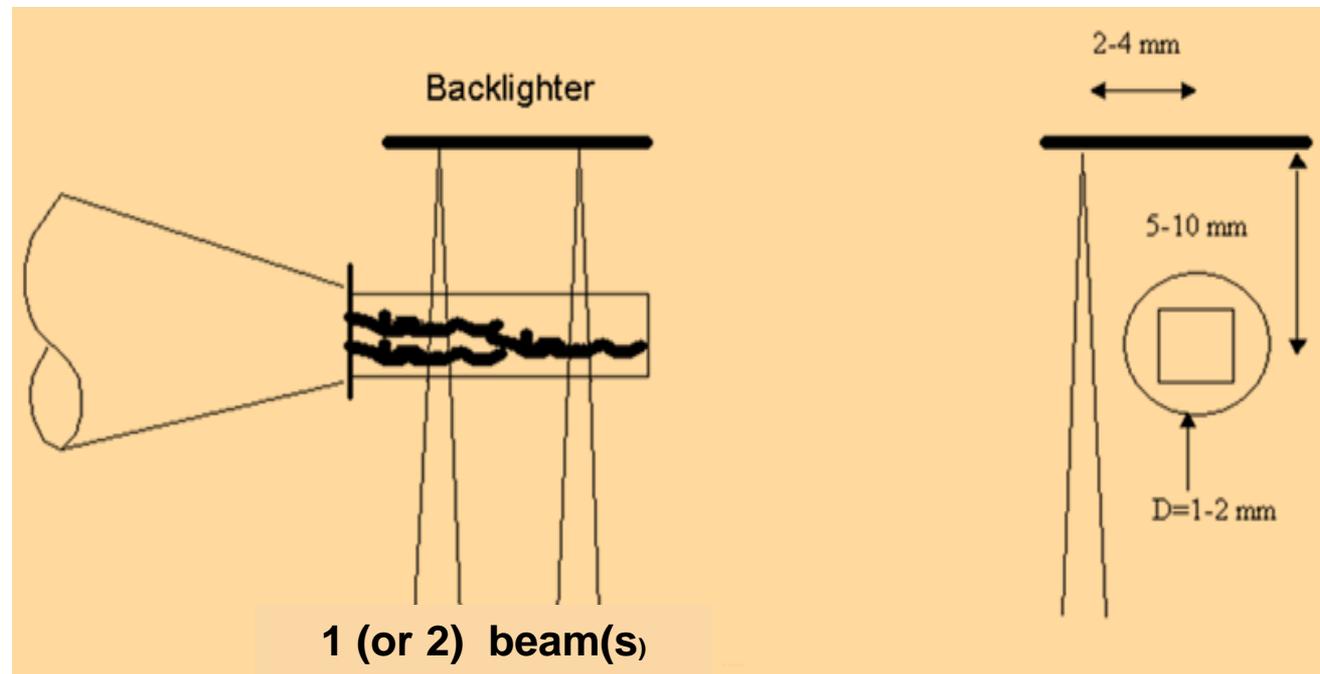
Velocity and  $n_e$  in low density plasmas.

## Optical Pyrometer

Temperature Measurement

## Radiography of the spatial structure by X-ray short pulse with :

1. X-rays : 100 eV - ...
2. Short duration: 10 ps. *The backlight should be lit by a short pulse (2-5 ps) to reflect the characteristic time of atomic physics and hydrodynamics.*
3. High luminosity (fluence), for good sensitivity.
4. Field  $\sim 1$  cm



Possibility of **splitting** the focal spot in two.

For the **ionization wave**, with 15 microns, it should be possible to observe flatness defects, instabilities, ...

→ in a first time: 10 - 20  $\mu\text{m}$

It would be interesting to see the **thickness of the shock**, a few microns.

→ term: 5  $\mu\text{m}$  if possible (with a lower field)

For **jets**, one has to focus on wide field camera

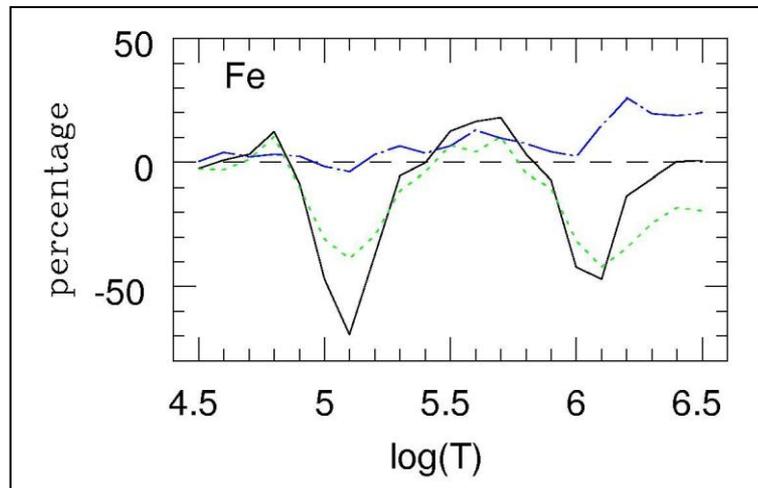
→  $L \approx 5 - 10 \text{ mm}$ .

With a 1024 pts camera, it corresponds to a **resolution** of 5-10  $\mu\text{m}$

# Opacity Measurements for Stellar Physics

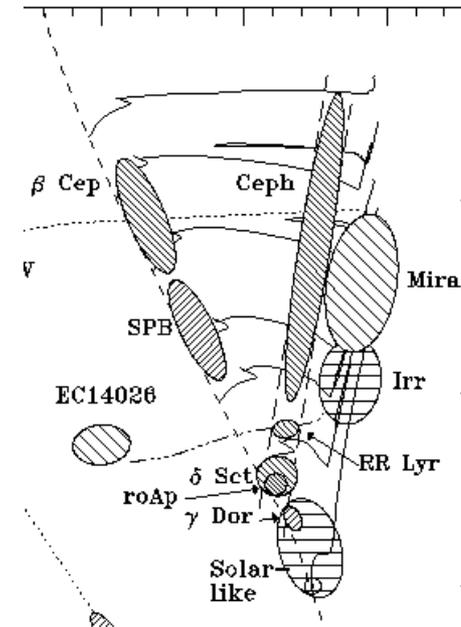
- Opacities control the radiative acceleration of elements in stellar envelopes → **differential stratification**

*Levitation of the most absorbent elements compared to those who are less absorbent.*



*Delahaye et al. 2008*

- Opacities control the «  $\kappa$ -mechanism » of pulsation of stellar envelopes.
- **Problem with the identification of modes ( $l=0$  ?  $l=1$  ? ... ) and thus their scientific exploitation.**



Pulsating stars observed by COROT, KEPLER

## Opacity measurements

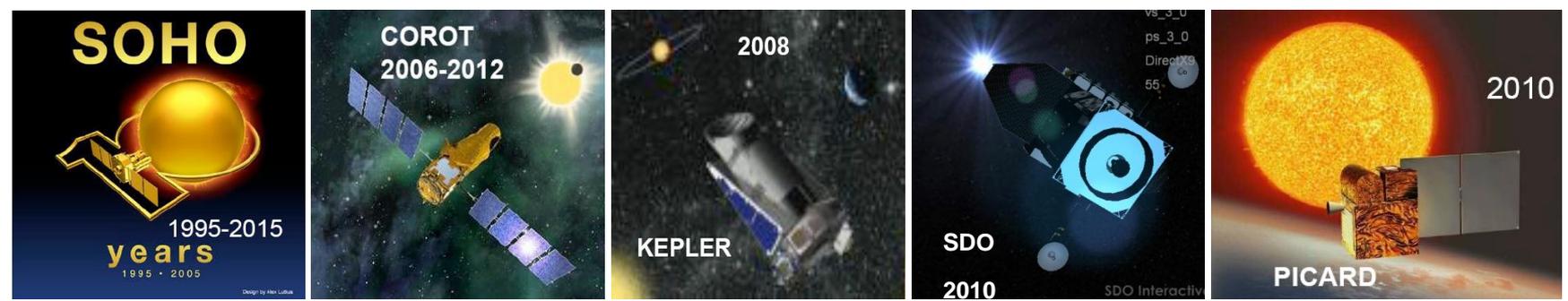
- of mixtures of elements with intermediate  $Z$  (C, N, O, Fe, ...)
- at low energy [15 eV – 100 eV]

Référence	Installation	Éléments	$T_e(eV)$	$\rho (g/cm^3)$	Gamme Spectrale (eV)
<a href="#">Davidson et al. (1988)</a>	Helen	Al	15 – 50	0.005-0.1	1300-1800
<a href="#">Perry et al. (1991)</a>	Nova	Al	58	0.02	1520-1610
<a href="#">Foster et al. (1991)</a>	Helen	Ge Al Mg	76	0.05	1200-1600
<a href="#">Bruneau et al. (1991)</a>	Octal	Ge	50	0.01	1180-1380
<a href="#">DaSilva et al. (1992)</a>	Nova	Fe	35	0.001	50-120
<a href="#">Springer et al. (1992)</a>	Nova	Fe	60	0.01	90-300
<a href="#">Eidmann et al. (1994)</a>	Astérix	Be B C Al	$T_e$	$\rho$	$< 1 keV$
<a href="#">Perry et al. (1995)</a>	Nova	Ge	38	0.012	1000-1600
<a href="#">Winhart et al. (1996)</a>	Asterix	Fe Ho Al	20	0.01	70-125
<a href="#">Springer (1997)</a>	Saturn	Fe	20	0.0001	65-90
<a href="#">Back et al. (1997)</a>	Nova	Ge Al	10 – 30	0.03	1200-1500
<a href="#">Merdji et al. (1998b)</a>	Asterix	Sm	5 – 20	0.004	1060-1160
<a href="#">Merdji et al. (1998a)</a>	Asterix	Al	20-30	0.003-0.01	1480-1550
<a href="#">Eidmann et al. (1998)</a>	Astérix	Au	20	0.01	50-300
<a href="#">Chenais-Popovics et al. (2000)</a>	Asterix	Fe	15 – 30	0.003	720-760
<a href="#">Chenais-Popovics et al. (2001)</a>	LULI	Al-Ni	15-30	0.001-0.01	860-1030 1480-1550
<a href="#">Chenais-Popovics et al. (2002)</a>	LULI	Ni	20	0.01	860-1085
<a href="#">Thais et al. (2003)</a>	LULI	Al	13-20	0.02-0.15	1480-1550
<a href="#">Bailey et al. (2003)</a>	Z	NaBr	50	$3 \times 10^{21}$ $cm^{-3} (n_e)$	1030-3100
<a href="#">Fujioka et al. (2005)</a>	Gekko-XII	Sn	30	0.01	65 -140
<a href="#">Renaudin et al. (2006)</a>	Phébus	Mg/Ge	45/58	0.02/0.012	1180-1550
<a href="#">Kontogiannopoulos et al. (2007)</a>	LULI	Al/ZnS	25/15	0.003	100-225
<a href="#">Bailey et al. (2007)</a>	Z	Mg Fe	156	$6.9 \times 10^{21}$ $cm^{-3} (n_e)$	800-1800
<a href="#">Loisel et al. (2009)</a>	LULI	Cu Fe Ni Ge	15-25	0.001-0.01	700-1550
<a href="#">Zhao et al. (2009)</a>	Shenguang II	Al	80	0.1	1530-1610

# Theoretical & Experimental Opacities for the Interpretation of Helio & Asteroseismic Probes

Helio/Astero simology establishes a tight link between  
 macroscopic and microscopic physics  
 astrophysical observations and laser experiments

... 5 satellites presently in operation ...



## Radiative zone

(where energy is transported by radiation)

**Low mass stars  $M < 1.5 M_{\odot}$**

*Interior conditions*

$T \geq 200 \text{ eV}$

$\rho \geq 1 \text{ g cm}^{-3}$

**Massive stars  $M > 1.5 M_{\odot}$**

*Envelope conditions*

$T \leq 100 \text{ eV}$

$\rho \leq 10^{-6} \text{ g cm}^{-3}$

} *Equivalent conditions*

$T \approx 15 - 40 \text{ eV}$

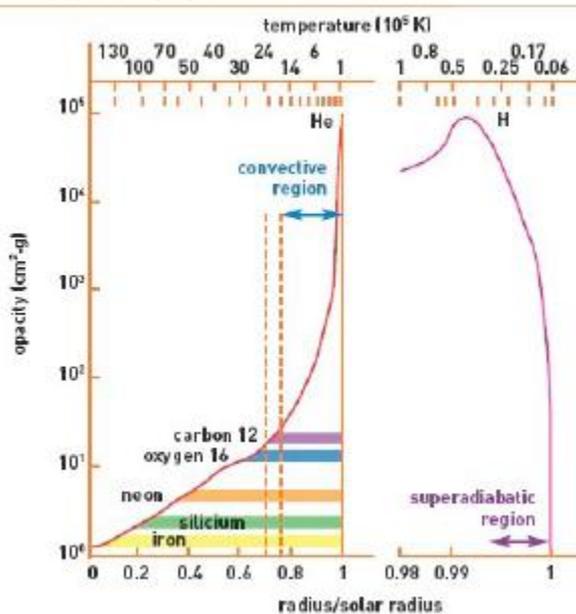
$\rho \leq 10^{-3} \text{ g cm}^{-3}$

# Opacity coefficients in the central radiative zones of solar-like stars

→ Contribute to a precise determination of the **central temperature** and of the **longevity** of stars.

$$\rightarrow \frac{\partial acT^4}{\partial r} = -3 \kappa_R \rho \frac{L}{4\pi r^2}$$

Solar case



35 elements presently included in calculations

Contributors to the opacity

Turck-Chièze et al. Phys. Rep. 230, 1993  
using Los Alamos library 1982

Lifetime of a 0.8 M<sub>⊙</sub> star with Z = 0.001 } 14.33 Gyr

Lifetime of a 0.8 M<sub>⊙</sub> star with Z = 0.02 } 22 Gyr

Livermore opacities Iglesias and Rogers 1996, 2000

OPAL tables can be done for different compositions

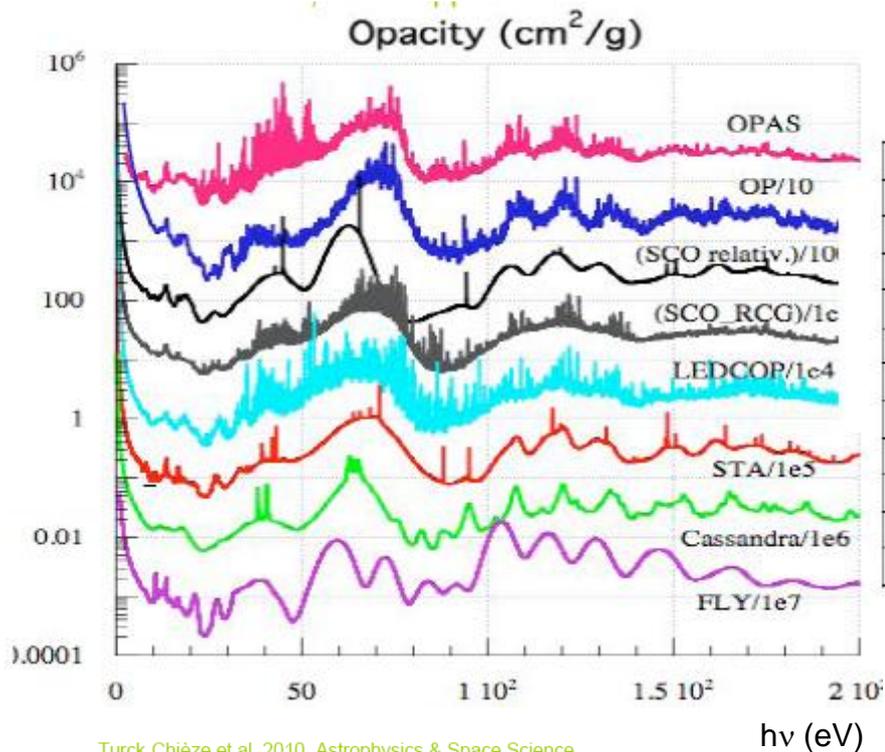
Spectra generally not distributed

$$\kappa_R = \int \frac{dB}{dT} d\nu / \int \frac{1}{\kappa_\nu} \frac{dB}{dT} d\nu$$

OP tables with spectra

Seaton et al., Badnell et al.

# Comparison of Fe Opacity Spectra among 7 teams including OP



Turck-Chièze et al. 2010, Astrophysics & Space Science  
 Gilles et al. 2010, A&A suppl.

OPAS and SCO-RCG  
CEA

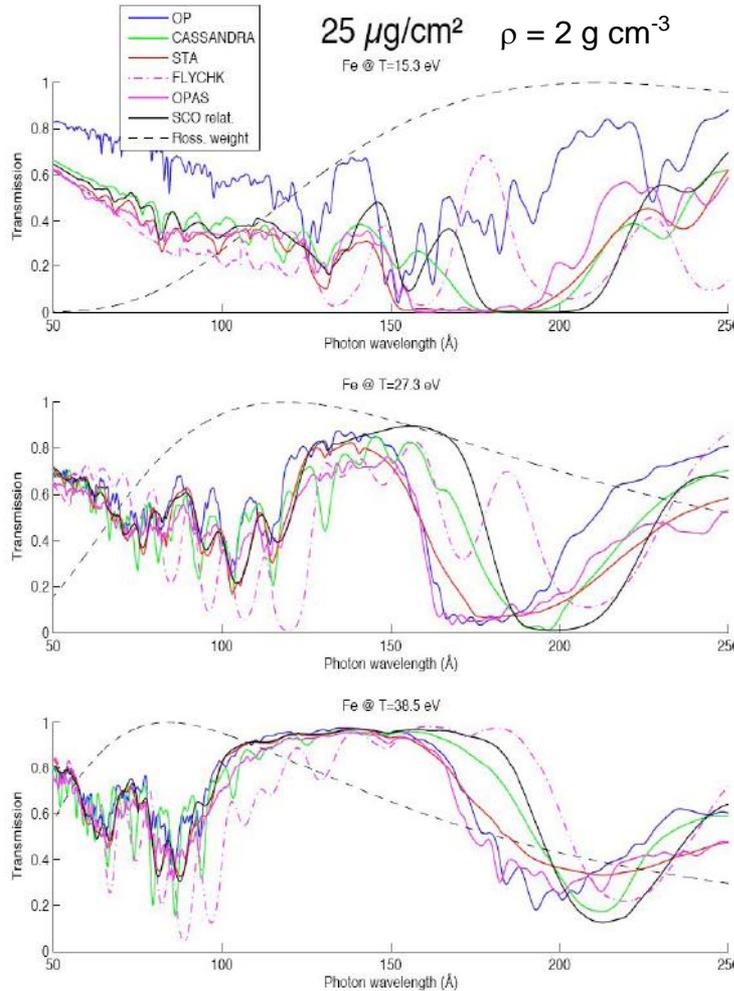
LEDCOP Los Alamos

Not Livermore !

	$\langle Z \rangle$	KR	KP
FLY-ETL	8.004	19850	37957
FLY-HETL	7.99		
OP	8.6	14642	28000
STA	8.544	20500 / 20500	33380 / 34090
AA Perrot	7.766		
AA-More	8.462		
CASSANDRA	7.858	20250	31250
OPAS	8.350	23323	36438
SCO Rel	8.472	15551	32286
SCO Non Rel		20875	33396
SCO-RCG	8.374	19335	30331

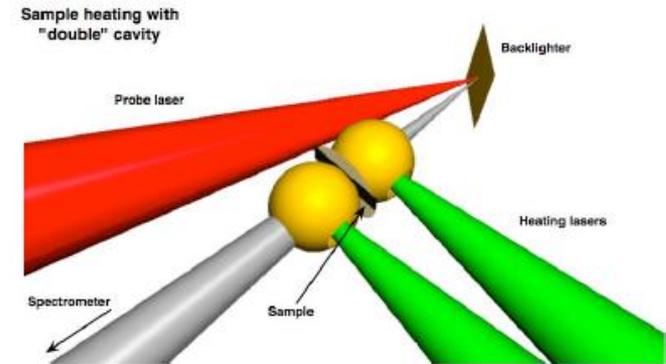
# Fe Transmission Spectra at Different Temperatures

$$k_x = \int \frac{dB}{dT} d\nu / \int \frac{1}{k_\nu} \frac{d\nu}{dT}$$



## Main experimental difficulties to overcome :

- Achieving the T- $\rho$  conditions with small gradients in the foil;
- Avoiding the saturation of spectra;
- Remaining near (... at) LTE.



# Opacity Measurements at Low Temperatures

Heating laser : 300 – 500 J, duration 0.5 ns

Probe laser: 5 – 10 J, duration 10 ps, with adjustable delay ~ 1.5 ns

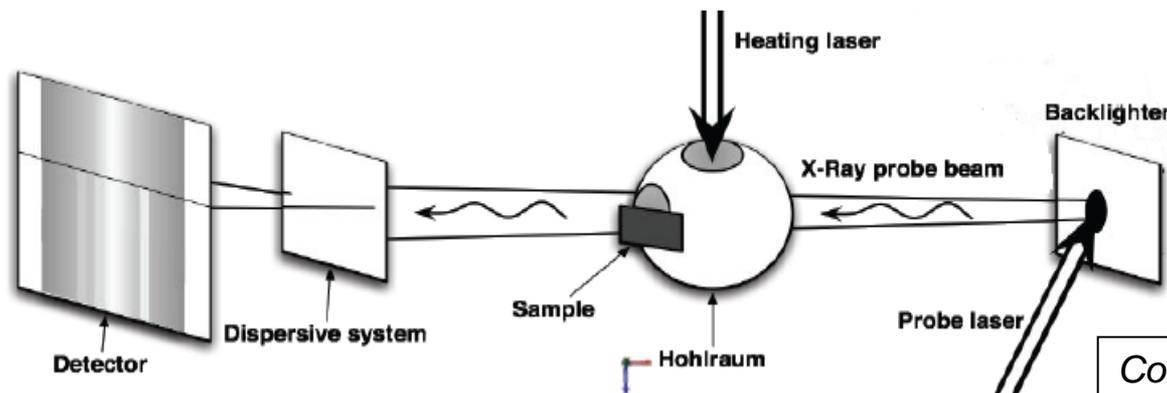
X or XUV spectroscopy with a streak camera

Backlighting radiography : wide spectrum

Direct radiative temperature measurements, through

$$E_{h\nu_{i=1,\dots}}^{obs}(t)$$

*An analogous of Dante*



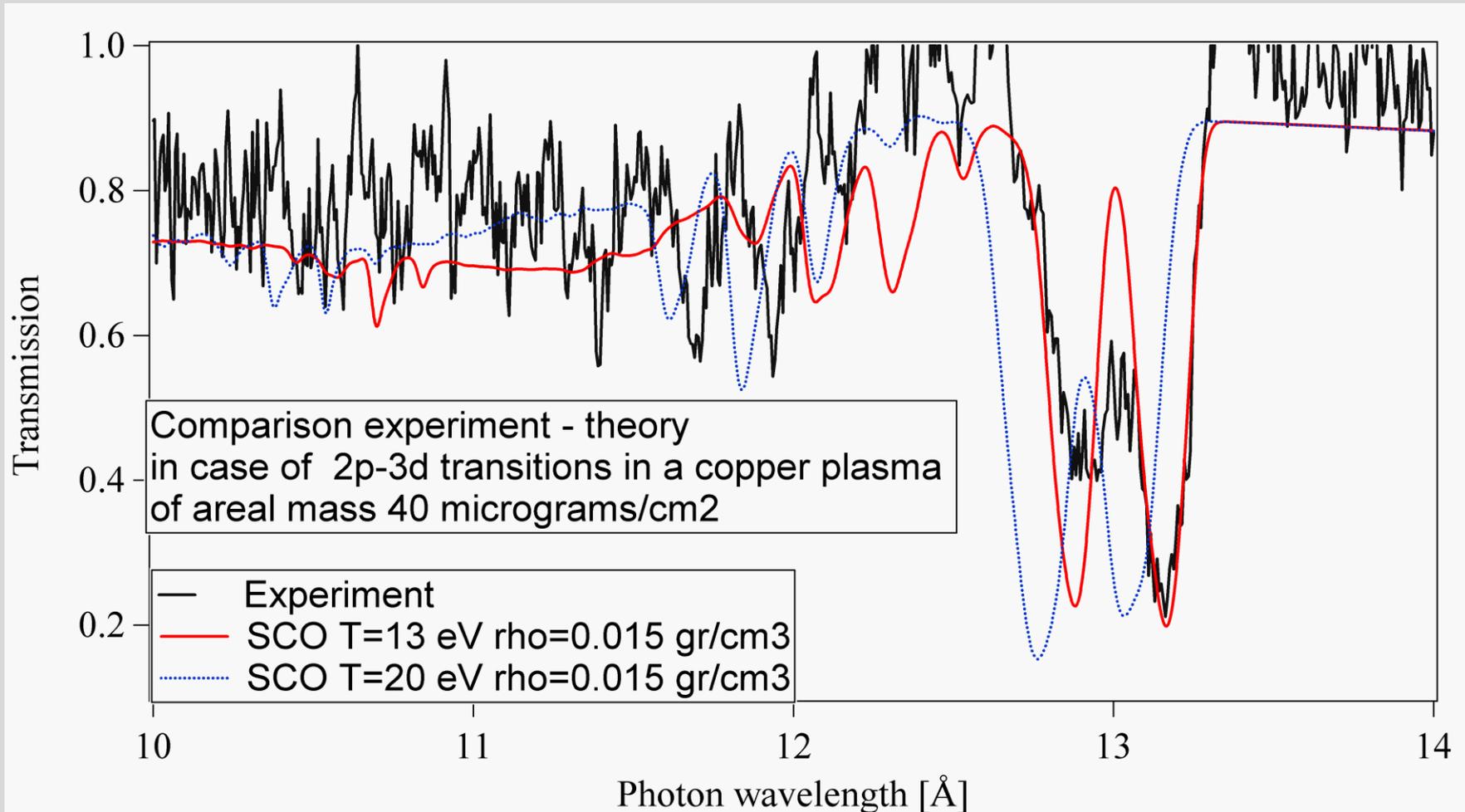
Principle of an opacity measurement

Loisel & al. 2008, 2010

*Collaboration*

- CEA/DSM (SAP et SPAM)
- CEA/DIF (DCSA et DCRE)
- LULI
- Max Planck Garching

# Comparison Experiment/Theory for Cu Opacity



# Concluding

*Laser produced plasmas are invaluable tools to put more and more physics in astrophysics.*

*Most subjects of « laboratory astrophysics » are relevant to IFE – and vice versa ...*

*If the production of plasmas with high energy densities and large volumes is highly desirable, the preparation of experiments and training rely on efficient, reactive, medium-sized facilities.*

**PALS with its team offer a brilliant example !**

*Thank you !*