Radiative shocks in astrophysical context

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ESF exploratory workshop XLA
Outline

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Introduction
Radiative shocks

In strong shocks in H, \[ T_{\text{shock}} \approx 1.5 \times 10^5 \left( \frac{v}{100} \right)^2 \text{ in } \text{K, km/s} \]

-> the hot gas radiates

The effect of the radiation on the shock structure depends on the opacity.

In practice: two numerical approaches

1. Radiation is considered only as a cooling mechanism
   -> radiative cooling included in the hydrodynamics equations as a sink term in the energy budget (optically thin case)

2. Radiation transport equations are solved simultaneously to give the flux, energy & pressure which are included in hydrodynamics equations (non optically thin case)
**A manifestation** of the coupling between hydro & radiation: **the radiative precursor**

When the **opacity** is large enough, the photons emerging from the shock front ionize the unshocked gas.

The radiative precursor can only be obtained with fully radiative hydrodynamical simulations.
Radiative shocks in astrophysics

STARS

**Interiors**: SN explosions; high velocity \((>10^4 \text{ km/s})\), high opacity, radiation pressure; rad. precursors; relativistic effects, **no observation**

**Envelopes/atmospheres** (cepheids): intermediate velocity (70 km/s), rad. precursors, indirect evidences (variability, spectro.)

**Accretion shocks**: high velocity (500 km/s), radiative precursors ?, indirect spectroscopic/photometric signatures, no images
Radiative shocks in astrophysics

MIS

Circumstellar envelopes: intermediate velocity (~20-40 km/s), rad. precursors, spectroscopic signatures, images.

SNR (~1000 km/s) interacting with « dense » ISM: rad. precursors, spectroscopic signatures, images

Bow shocks of high velocity stellar jets (> 200 km/s): rad. precursors, spectroscopic signatures, images

... and also in galaxies
**INTRODUCTION**

**Topology/geometry**

### Are really the shocks 1D?

**CO shell around carbon star TT Cygni, IRAM**

(from Olofsson et al AA 2000)

**Spherical accretion shock of protostellar formation**


(interaction of SNR 1987A with ISM in nov 2003, HST (credit NASA))

Present expansion $v \sim 4000$ km/s, glowing mass $\sim 0.1 M_\odot$, width of the equatorial ring $\sim 10^{17}$ cm, $n_H = 3 \times 10^3 - 3 \times 10^4$ cm$^{-3}$, velocity of the shock in the ring several 100 km/s

CO shell:

- 0.007 $M_\odot$, clumps, $v \sim 20$ km/s
- width $1.9 \times 10^{16}$ cm, $n_H = 250$ cm$^{-3}$

(location at $\rho \sim 10^{10}$ g/cm$^3$, $T \sim$ several $10^3$ K, several 100 km/s for $1 M_\odot$, Stahler et al ApJ 1986, Winkler et al. ApJ 1980)
Selected examples
Stellar accretion shock in CTTs

- low mass \((M \sim 1-2 \, M_\odot)\)
- young \((\sim 10^6 \, \text{yrs})\), PMS stars
- slow rotators \((v_{\text{sini}} \sim 10-20 \, \text{km/s})\)
- spectroscopic & photometric variability
- UV & IR excesses, X ray emission
- \(B \sim 1-2 \, \text{kG}\), spots.

- accretion disk
- huge bipolar jets \((100 \, \text{km/s}, \text{parsec})\)

Accretion along 3D structures connecting the disk to the star \((10^{-6} \, M_\odot/\text{yr})\):

- Stable magnetospheric columns
- Unstable tongues (KH/RT instabilities)
Accretion signatures

- -> continuum excess (veiling) in blue and UV
- -> X ray emission.

From Bertout et al, APJ 1988

X ray spectrum of T Tau (XMM/RGS)

From Guedel et al, AA 2007

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Stellar accretion shock in CTTs

- **Dynamics of the accretion flow**: free fall velocity
  \[ v_{\text{ff}} \sim (2 \frac{GM}{R})^{0.5} \rightarrow 400 \text{ km/s} \] (for \( M = 1 \, M_\odot \), \( R = 2 \, R_\odot \))

- **Accretion shock is close to the surface**
  Highly supersonic: for \( T_* \sim 5000 \, K \) \( \rightarrow M = 70 \) (strong)
  Shock temperature \( T_{\text{shock}} \sim v_{\text{ff}}^2 \sim 2 \times 10^6 \, K \) (X ray emission)

Depending on the opacity, the structure and signature of the shock may differ (presence of a radiative precursor?)
Stellar accretion shock in CTTs


At the base of the column:
\[ T_{\text{shock}} \sim v_{\text{ff}}^2 \sim 10^6 K \quad (@300 \text{ km/s}) \]
\[ \rho = 5 \times 10^{-11} \text{ g/cm}^3 \quad (N_H \sim 10^{13} \text{ cm}^{-3}) \]

Opacity: \( \kappa R^* \sim 0.35 \) (taken from OP)

- \( T_* = 4000K \)
- \( R_* = 2 R_\odot \)
- \( M_* = 0.8M_\odot \)
- \( M_{\text{dot,acc}} = 10^{-7} M_\odot/\text{yr} \)
- \( R_{mi} = 2.2 R_* \)
- \( R_{mo} = 3 R_* \)
Shock location

then $P_{\text{ram}} \sim P_{\text{therm}}$

*close to the surface, but*:

below the surface:
(Gunther et al 2007)?

or above the surface:
(most commonly assumed)?

Depending on the shock location (i.e. respective to the surface), the opacity will change and the regime of the radiative transport will differ (radiative precursor?)
Another example: the bow shocks of YSO jets

High $v$ (> 100 km/s) -> strong bow shock at the head of the jet.

Radiation is mostly included by cooling energy losses only.

In few cases a precursor is observed, but attributed to magnetic shock structure.

**However**

Radiation from the shock *preionizes the gas*, as seen already from simulations of Raga & al. for a jet velocity of $\sim$ 200 km/s

*(Raga et al 99)*

Temperature, ion+atom and neutral H at the top of the jet with and without radiative transfert *(Raga et al 99)*

**Typical dimensions** $10^{16}$ cm,
neutral jet: density $n = 225$ cm$^{-3}$, $v \sim 267$ km/s, $T = 1000$ K
ambient medium: density $n = 25$ cm$^{-3}$, $T = 1000$ K

* C. Stehlé, Obs. de Paris, Sept. 24-25 2008
Bow shocks of YSO jets

Radiation transport reduces $T$ at shock front by $\sim$ a factor 2
($3 \times 10^5$ K instead of $7 \times 10^5$ K)

$T(K)$, ion+atom and neutral H, along the z axis, at the top of the jet with and without radiative transfer (Raga et al 99)
Bow shocks of YSO jets

Radiation transport reduces $T$ at shock front by $\sim$ a factor 2 ($3 \times 10^5$ K instead of $7 \times 10^5$ K)

Softer X ray emission

This effect increases with the jet velocity.

Observations (Pravdo et al 2004) with Chandra on HH 80 and HH 81 ($v \sim 600$ km/s) give a slower shock temperature (and thus deduced velocity) than deduced from visible observations.
A large variety of radiative astrophysical shocks:

- importance of **radiation** (opacity/cooling), *which means chemical composition, temperature on hydro and structure*

- importance of **geometry**, also connected to opacity (*optical depth*).

- question of **dynamics**: stationarity, stability

- **magnetic field** effects

- **3D radiative transfert** (*photometric and spectroscopic signatures*).

A lot of **theoretical** studies but insufficient **experimental** studies
Experimental studies of (non optically thin) radiative shocks
Why experiments

(1) study astrophysical hypersonic shocks is **impossible** (*dimensions and time*)

(2) scale astrophysical radiative shocks on laboratory: too many parameters, **academical** interest only.

(3) Study the topology, dynamics, stability, spectroscopic and photometric signatures to understand the **physics** of shocks

(4) **Validate simulations**
What as been done

“Conventionnal” shock tubes : $M < 10$

higher $M$ on HEDP installations (lasers and pinches)

Sustained “1D” radiative shocks

Blast waves
  stability \((Grunn 1991, \text{tentative by Edwards 2001})\)

Blast waves in more complex geometries
  collision of blast waves \((R. Smith’s talk)\)
1D Radiative shocks: the objective is to obtain

(1) strong sustained shocks (M>>1) in gases
(2) with a strong impact of the radiation.
(3) in a simple geometry (1D)
(4) on laboratory scales

This has been achieved on high energy laser installations, like:
LULI (60J, 1ns), PALS (200 J, 0.3 ns) and Rochester (4000J, 1ns)
Principle of radiative shock generation

The laser is focalized on a foil which converts the radiation energy into mechanical energy.

Target

Millimetric scales,

Gold = 0.5 µm
CH = 10 µm
Typical setup

-> **1D geometry**: cylindric or parallelepipedic target (mm scale)

-> shock launched by a piston with ~ **constt velocity**

-> **high Z gas (xenon)** favorable to radiation

-> **moderate/low pressures** $\rho \sim 10^{-4}$ g/cm$^3$ (opacity adjustments)

$$\tau = 1 \text{ (for 1 mm, xenon @ 300K)} \rightarrow \rho = 5 \times 10^{-4} \text{ g/cm}^3 \text{ (0.1 bar)}$$

<table>
<thead>
<tr>
<th>Location</th>
<th>Speed (km/s)</th>
<th>Density (g/cm$^3$)</th>
<th>Energy (J)</th>
<th>Duration (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LULI</td>
<td>60</td>
<td>$5 \times 10^{-4}$</td>
<td>60</td>
<td>1</td>
</tr>
<tr>
<td>PALS</td>
<td>55</td>
<td>$5 \times 10^{-4}$</td>
<td>200</td>
<td>0.3</td>
</tr>
<tr>
<td>Rochester</td>
<td>150</td>
<td>$6 \times 10^{-3}$</td>
<td>4000</td>
<td>1</td>
</tr>
</tbody>
</table>

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in 1D shocks:

1. the shock in Xe is in the supercritical regime (T identical before and after the discontinuity).

2. High compression >4 (strong shock with radiation and ionization effects)

3. Te ≠ Ti in the front

Experimental studies of radiative shocks

Extended radiative precursor
deduced from visible time resolved interferometry

Bouquet S., Stehle C. et al., PRL 2004
Fleury et al., LPB 2002

Streak camera, slit // shock propagation

Probe green laser (one arm)

$N_e$, velocity of the shock ($\sim 60 \text{ km/s}$) and precursor ($\sim 130 \text{ km/s}$) in qualitative agreement with 1D simus.

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From 1D simulations, one expects 3 phases for the precursor:

- a rapid launching phase ($v_{\text{prec}} > 400 \text{ km/s}$) in the first 20 ns
- a deceleration during 100 ns ($v_{\text{prec}} \sim 100 \text{ km/s}$)
- the stationary limit at ~ 400 ns.

**Experiments**

- less acceleration in the launching phase \((\text{Fleury \& al, LPB 2002, Bouquet \& al. PRL 2004})\).
- more pronounced slowdown than expected from 1D, \((\text{González et al. LPB 2006})\).
- earlier convergence towards the stationary limit \((\text{Stehlé et al, in prep})\).
Experimental studies of radiative shocks

**Shock deformation** (compared from expected 1D)

observed

by **time resolved transverse visible interferometry1D image** on the slit of a streak camera (Stehlé et al, in prep)

(xenon cell, 0.1 bars)

also observed by **instantaneous 2D imaging**:

- XUV radiography *(Reighard et al. POP 2006)*,
- Gated Optical Imaging *(Vinci et al., Jphys IV 2006)*

\[
\text{Streak camera, \ slit } \perp \text{ shock propagation}
\]
2D effects
2D effects in the radiation transport

If the shock fills the tube section, the pure hydro is 1D.

But the photons “escape” laterally (are lost) from the tube when $\tau_{\text{lateral}} = \kappa d \ll 1$.

Thus 1D radiation transport is valid when $\tau_{\text{lateral}} = \kappa d \gg 1$.

In these radiative shocks experiments, $\tau_{\text{lateral}}$ may be smaller than 1.

Influence of boundary effects for radiation.

Radial radiation losses induce departures from 1D.

(Leygnac et al., PoP 2006)
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HERACLES Simulations indicate a shock curvature

(half) maps of $\rho$(g/cm$^3$) & $T$ (eV)
50 ns after PALS laser arrival, in a xenon cell
(0.2 bars, 0.7 x 0.7 cm, walls albedo of 40%).
Distance taken from the pusher in mm

$V$ shock
~50 km/s

González et al. LPB 2006
Boundary conditions for radiation

**Radiative losses: albedo** $a$ (% of radiation reinjected in the gas by the walls)

- $a = 100\%$, mimics the 1D scenario: all the photons are “reinjected” inside the tube. The shock front will be planar. *(shocks in stellar envelopes)*

- $a = 0\%$, all the photons are lost at the walls. The shock front is curved. *(astrophysical shocks of finite section, accretion funnels)*
Precursor extension

A small albedo (strong losses):

- Slows down the precursor and diminishes the distance between the radiative and shock fronts.
- Reduces the time which is needed to reach the stationary limit.

HERACLES 2D simulations of the positions of precursor and shock fronts in the conditions of PALS experiments:

- Parallelipipedic target $0.7^2 \times 4\text{mm}$
- $\text{Xe} \text{ at } 0.2\text{bar, } v_{\text{shock}} \sim 60\text{km/s}$

Experimental results recovered with an albedo of 40%
Expected photometric signatures
**Anisotropy of the shock luminosity**

HERACLES simulations show that the angular distribution of the flux is *peaked* at an angle *which depends on the albedo*:

- $\pi/2$ for $a=0$ (fully transparent windows)
- $\sim 0$ for $a=100\%$ (fully reflective windows)

**Experimental conditions of PALS experiment** (xenon, 0.2 bars, $v_{\text{shock}} \sim 50 \text{ km/s}$)

*Normalized luminosity at 50 ns for different values of albedo* (70% red, 50% green, 0% black).

*M. González et al., submitted to A&A*
Anisotropy effects on the photometric signature of accretion shocks?

( the angle of observation varies during the rotation )

Anisotropy of the shock luminosity

that the angular distribution of the flux is *

*peaked* at an angle *which depends on the albedo*:

\[ \frac{\pi}{2} \text{ for } a=0 \text{ (fully transparent windows)} \]

\[ \sim 0 \text{ for } a=100\% \text{ (fully reflective windows)} \]
Spectroscopic signatures

1D shock structure obtained with 1D code
1D radiative transfer post-processing (on line calculated EOS & opacity)

Strong structures in absorption (cold gaz in front of the shock) near 10 eV
Conclusions
Conclusions

Radiation hydrodynamic needed for several astrophysical shocks

3D effects affect the structure of the shock

Knowledge of the initial and boundary conditions of the shocks are very important

3D radiative transfer may be mandatory

The numerical modelling has to be improved (non grey approximation, NLTE).

Experiments allow to constrain the simulations and the knowledge of these complex phenomena.
Perspectives

✓ Develop new experimental spectroscopic studies of radiative shocks

✓ Study the impact of the informations gained in the lab. studies on the structure, dynamics and photometric signatures of stellar radiative shocks.

ANR STARSHOCK
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