ELECTROMAGNETICALLY-LAUNCHED STRONG SHOCKS RELEVANT FOR ACCRETION SHOCKS IN ASTROPHYSICS: Experimental study and numerical approach

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Strong shocks are present in various astrophysical contexts:

- From stellar infancy where matter is accreted from the stellar disk to the young star and ejected in the form of powerful plasma jets,
- Up to stellar supernovae explosion in their final stage.

Shock topology and dynamics is quite complex. Besides this, it is strongly influenced by radiation.

Therefore shock study is a potential candidate for probing into various astrophysical processes.
Rationale

• Laboratory plasma astrophysics is a powerful tool to study the dynamics of hypersonic processes.

• Till date, such laboratory astrophysics studies are mainly performed on large-scale laser facilities, addressing pure hydrodynamic radiative shocks, at very high velocity (50 - 150 km/s) and moderate pressure (0.1 - 1 bar).

• Complementary to laser experiments, compact pulsed power generators can drive astrophysically relevant shocks in low pressure noble gases [K. Kondo, et al., 2006].

• Moreover, the electromagnetically driven shock waves may have larger scales than those produced by laser; thus they can be observed rather easily [K. Kondo, et al., 2008].

- We intend to extend the study to a wider class of shock regimes
  - at velocities (10 – 30 km/s) and
  - at low pressures (few mbar)
I have optimized a dedicated experimental setup, based on high energy electrically pulsed device.

The main aim is to design, to implement and to exploit a comprehensive suite of diagnostics of the shock plasma.

Thus, I am contributing to the development of a new table top electric generator including the implementation of new diagnostics.

In parallel, this year, I will participate in a 5 weeks experimental campaign on PALS laser facility in Prague to study:

- The spectroscopic signatures of laser-driven shock waves (~ 60 km.s\(^{-1}\))
- The collision of two laser-driven shock waves (+ / - 50 km.s\(^{-1}\)).

Finally, data obtained from aforesaid experiments will be used to test a model of the shock.
Device: Electromagnetic shock generator

Scheme of the electrical circuit and of the plasma gun. The installation of optical fibers allows looking radially at the plasma moving in the shock tube.

Transverse interferometry and imaging will be implemented too.

Equivalent capacitance $C = 12 \ \mu F$
Charging voltage = $15 - 30 \ kV$
$R_{cir} = 1 \ m\Omega$ and $R_{damp} = 0 - 2 \ ohm$
$P = 0.1 - 10 \ mbar$

Two coaxial conical electrodes and plasma sheath which is guided along the direction of magnetic pressure $P_{mag}$, represented by red arrows.
Optimization: Input parameters and results

The reference values describe the optimized device with Ar or Xe backing gas.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reference Value</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half angle of the cone</td>
<td>15°</td>
<td>13°, 14°, 15°, 16°, ………. 24°</td>
</tr>
<tr>
<td>Accretion factor, $\varepsilon$</td>
<td>0.4</td>
<td>0.1, 0.2, 0.3, ………. 0.9</td>
</tr>
<tr>
<td>Pressure, $P$</td>
<td>100 Pa</td>
<td>10, 20, 50, 100, 200, 500, 1000</td>
</tr>
<tr>
<td>Damping resistance, $R_{damp}$</td>
<td>0 ohm</td>
<td>0, 0.1, 0.2</td>
</tr>
</tbody>
</table>

For Ar, Time dependence of the main parameters according to the circuit model: (a) current (kA) and voltage (V), (b) accreted mass (kg) and rate of accretion (kg/s), (c) speed (m/s) and kinetic energy (J).
Laser Driven Shock: Experimental Setup

Drive beam
- \( E = 60 \text{ J} \)
- \( \lambda = 1.315 \text{ m\( \mu \)m} \)
- \( \tau = 350 \text{ ps} \)
- \( \phi = 300 \text{ m\( \mu \)m} \)

MAIN + Prepulse
- \( E = 500 \text{ J} \)
- \( \lambda = 1.315 \text{ m\( \mu \)m} \)
- \( \tau = 350 \text{ ps} \)

Xe cell

XRL laser,
- \( \lambda = 21.2 \text{ nm} \)
- 3 mJ
- 0.2 ns

Zn target

Not to Scale!

X-ray radiography at 21.2 nm

From Chaulagain et al. (2015)
The target and the shock tube

Double layer:
CH (10 μm) and Au (0.5 μm)

Ultrathin 0.15μm SiN window *see through*

Thick Si window *opaque*

Al wall *opaque*

0.3ns 60 J IR laser

xenon gas

0
0.5mm
~1.5mm
z
The shock generation

Double layer:
- CH (10 μm) and Au (0.5 μm)

Ultrathin 0.15 μm SiN window
- see through

Thick Si window
- opaque

xenon gas

Al wall
- opaque

0.3ns 60 J IR laser

foil acceleration

rocket effect

piston entering Xe z=0

shock formation z ~ 0.3mm

shock propagation z < 2.5mm

0.3ns 60 J
IR laser

$\text{t = 0ns}$
The shock motion

plasma

xenon gas

t ~ 10 ns
The shock motion (cont’d)

plasma

xenon gas

$\text{t \sim 15 \text{ ns}}$
The shock motion (cont’d)

t ~ 20 ns

plasma

xenon gas
Target side view and instantaneous XRL imaging

Transmission, $T = \frac{I_{\text{Shock}}}{I_{\text{Reference}}}$

Zoom of the shocked region

Scales in $\mu m$

Time: 20 ns

$\Delta t = 0.2$ ns

Chaulagain et al. (2015)
Optical Depth ($\tau$)

\[ T = \exp(-\tau) \]
\[ \tau \text{ is optical depth and } \tau = - \ln (T) \]

We have estimated the optical depth (varies from 0.5 to 2.5) with this equation.

From the optical depth we can calculate the absorption coefficient of the plasma using Abel Inversion.
Abel inversion of a transmission image

The Abel inversion is an integral transform which will allow to derive, for the image of an object presenting a cylindrical symmetry, the value of the local absorption coefficient $k(r)$ (1/cm) from the optical depth $\tau(x)$ along the direction $y$.

$$k(r) = -\frac{1}{\pi} \int_{r}^{r_0} \frac{\tau'(x)dx}{(x^2 - r^2)^{1/2}}$$

The observations give $\tau(x)$ as a number of points. Therefore, these values can be introduced in the calculations as a sequence of readings, $\tau_k$.

$$k(j) = r_0^{-1} \sum_{k=0}^{n-1} a_{jk} \tau_k$$

$x_k = kr_0/n; \ (k=0, \ 1, \ 2, \ ... \ , \ n-1)$, where $r_0$ is the boundary radius. Then, a number of values of $k(r)$, called $k_j$ corresponding to $r_j = j r_0/n \ (j=0, \ 1, \ 2, \ . \ . \ . , \ n-1)$.

Bockasten et al., 1960.
Absorption coefficient (k)

- Cylindrical or spherical symmetry is the necessary condition for applying Abel. In our case, the image is not perfectly symmetric.
- Therefore, for deriving the absorption coefficient, we symmetrize the optical depth image (by slit rotation, cropping from the middle).
- In this way, we get two symmetric images which we have used as input for the Abel inversion.
- The Abel inverted image gives the absorption coefficient of plasma.
Planned laser experiments (spring 2015)

Still in Xe 0.3 bar

Ultrathin 0.15µm SiN window
see through

Thick Si window

Thick SiO2 windows
see through
I am studying strong shocks in laboratory astrophysics using multiple approach.

The electrical approach consists in launching a plasma layer by magnetic pressure.

- The parameters of a low-inductance and compact pulsed power device have been optimized with a circuit model.
- The results show that a set of electrical and geometrical parameters is ensuring a satisfactory behavior for Ar and Xe backing gases. Both gases will be used on a table top device delivering up to 5 kJ in 1 µs.
- Passive observations of the moving plasma, using side-on detection of the visible emission, give features coherent with the model.
- Time resolved UV-visible interferometry and spectroscopy are under implementation.

Laser driven shocks are generated by launching a massive piston into a dense gas.

- I have treated previous XRL projection radiographies of single shocks by introducing a local opacity and an Abel inversion technique.
- A campaign is planned in spring 2015 to study single shocks.
Conferences & Publications

Conferences:
- HELDA 2014: Presented a poster entitled “Optimization of an electromagnetic generator for strong shocks in low pressure gas”.
- Plas@Par industry day 2014: Presented a poster entitled “Electromagnetic generation of strong shocks in low pressure gas”.

Publications:
Merci pour votre attention