Laboratory astrophysics studies with magnetized laser-produced plasmas

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ASTROPHYSICAL CONTEXT
Mass accretion onto Classical T Tauri Stars

Accretion shock

Hot continuum emission ($T \approx 8,000$ K; some narrow lines; X-rays?)

Broad emission lines ($T \approx 10^4$ K)

Accretion flows

Inner hot dust wall

Inner gas disk

Disk wind/jet

Low-velocity disk wind?

Dusty disk

image credit: Hartmann+ ARAA 2016
Mass accretion onto Classical T Tauri Stars

Magnetospheric accretion

How much mass is accreted?
Mass accretion rate can be derived from excess luminosity and the knowledge of stellar mass and radius.

image credit: Hartmann+ ARAA 2016
Mass accretion onto Classical T Tauri Stars

Magnetospheric accretion

How much mass is accreted?

Mass accretion rate can be derived from excess luminosity and the knowledge of stellar mass and radius.

However not much is known observationally about the dynamics of the impact of the accretion flow onto the photosphere/chromosphere.

image credit: Hartmann+ ARAA 2016
Impact dynamics: cooling instabilities, fibrils and 3D

1D simulations

Cooling instabilities induces oscillation of shock front → not observed

2D simulations

Inside the column: independent fibrils
At the edge: splash out of plasma

3D simulations

Global structure. No resolution of shock.

Images: Matsakos+ 2013; Orlando+ 2010 ; Romanova+ 2004
LABORATORY MODEL OF MAGNETIZED ACCRETION COLUMNS

Results presented from:

Revet et al, 2017 Science Advances
Khiar et al, to be submitted to MNRAS
Laboratory model of an accretion column

**Experiments**
ELFIE 100 TW laser (LULI, Ecole Polytechnique)
- energy 40 J ($I_{\text{max}} \sim 1.6 \times 10^{13} \text{ W cm}^{-2}$)
- pulse duration 0.6 ns
- laser wavelength 1.057 $\mu$m
- focal spot diameter $\sim 700 \mu$m
Laboratory model of an accretion column

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Laboratory modelling
GORGON: single fluid, 2-T, 3D resistive MHD
[Chittenden+ PoP 2004; Ciardi+ PoP 2007; Khiar+ PoP in preparation]
- laser transport
- anisotropic thermal conduction
- optically thin radiative losses
- computational "vacuum"

Astrophysical modelling
PLUTO: single fluid, 1-T, 2D MHD
[Mignone+ 2007]
- anisotropic thermal conduction
- optically thin radiative losses
Laboratory "accretion flow"

time = 20 ns
Laboratory "accretion flow"

Laser-ablated plasma → "accretion flow" is well characterized
Impact onto the surface

- Formation of a reverse shock in the incoming stream
- Post-shock plasma pushes out the magnetic field and it is then re-collimated along the sides of the accretion flow forming a "cocoon" → strong perturbation of the accretion shock
Typical plasma conditions

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<thead>
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<th>Parameter</th>
<th>Value 1</th>
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<tr>
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<td>$1 \times 10^{-2}$</td>
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Shocks, cores, shells and cocoons...

- Electron-ion equilibration time-scale ~ 30 ns
  - Decoupled $T_e$ and $T_i$ ~ $m_i v^2/k_B$ ~ 5 - 10 keV

- Two components:
  → cold, dense core and hot, tenuous shell
Rayleigh-Taylor interchange instability

→ Radial "leakage" of post-shock plasma
Experimental platform ELFIE 100 TW @ LULI

**Laser**
ELFIE 100 TW laser (LULI, Ecole Polytechnique)
(40 J, 0.6 ns, 1057 nm, $\Phi \sim 700 \mu m$, $I_{\text{max}} \sim 1.6 \times 10^{13} \text{W cm}^{-2}$)

**Magnetic field**
Pulsed-power (20 kA, 16 kV) + Helmholtz coil (design and manufacture LNCMI Toulouse)
$B$ up to 40 T over > 1 microsecond
(Albertazzi+ RSI 2013)
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Diagnostics
- Electron density (Mach-Zehnder interferometer, 100 mJ in 350 fs @ 528.5 nm)
- Time and space resolved visible self-emission measurements (Streaked Optical Pyrometer)
- Temporally-integrated, spatially resolved X-ray emission (H- and He-like fluorine ions), FSSR.

Targets made of different materials:
- PolyVinyl Chloride (PVC, $(C_2H_3Cl)_n$)
- Teflon $(CF_2)_n$.
Experimental results: \( I \sim 10^{13} \text{ W cm}^2 \) \( B = 20 \text{ T} \)

**Laser interferometry**
- upon impact, generation of a shell of plasma surrounding a denser core
- at later times (> 50 ns) "cocoon" of post-shock plasma interacts and disrupts incoming flow.

Core \( n_e \sim 10^{19} \text{ cm}^{-3} \)
Shell \( n_e \sim 3 \times 10^{18} \text{ cm}^{-3} \)
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**SOP show three distinct regions:**
- incoming flow (the stream)
- core (+ shell)
- shell

![Interferometry: electron density](image)

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**FSSR data best fitted with two-component plasma**
- shell: $\sim 250 - 400 \text{ eV with } n_e \sim 4.2 \times 10^{18} \text{ cm}^{-3}$
- core: $\sim 50 - 100 \text{ eV with } n_e \sim 2.3 \times 10^{19} \text{ cm}^{-3}$
Simulations of Classical TTauri accretion flows

Structures similar to those seen in laboratory flows
- Core and magnetically confined shell of plasma $\rightarrow$ absorption of by shell of shock emission
- No temperature decoupling:
  - hot core
  - colder shell
- **Caveat**: gravity becomes non-negligible over time-scales $> 1000$ s

Simulated parameters of the accretion flow
- density $\sim 10^{11} \text{ cm}^{-3}$
- velocity $\sim 500$ km/s
- magnetic field $\sim 7 - 50$ G
- Temperature $\sim 2000$ K
- Post-shock plasma-beta $\sim 1-100$
Chromospheric ablation and ejection

- Chromosphere is ejected alongside with the post-shock accretion plasma → heating

- Experiments/simulations also show obstacle material being ablated and mixed

**laboratory experiments**

**FSSR data**

- PVC
  - With obstacle: 1st target material, Obstacle material
  - Without obstacle: With B-field, Without B-field

**laboratory simulations**

- ***Accretion flow***
- ***Obstacle***

**astrophysical simulations**

- Log $n_e$ (cm$^{-3}$)
  - 1000 s
  - 1250 s
  - 1650 s

- $z$ [10$^9$ cm]
  - $r$ [10$^9$ cm]
Summary and conclusions

Experimental confirmation of 2D astrophysical simulation results
→ formation of a multicomponent structure: core, shell and cocoon
→ feedback perturbs the accretion flow and shock
→ no gravity (astro sims. done with and without). Limited to early impact dynamics (unsteady accretion flow)

Rayleigh-Taylor-type interchange instability can develop in the accretion and post-shock flow
→ 2D modelling is not sufficient
→ wider spreading of post-shock plasma, interaction with corona (enhanced local heating?)

Mixing of chromospheric plasma with post-shock accreted flow
→ accurate treatment of chromosphere (obstacle) boundary conditions is necessary to correctly capture the post-shock flow dynamics
Summary and conclusions

Where can the experiments help?

→ time-variable accretion (multiple laser beams)
→ simulations are limited to plasma-beta not too far from 1 (and so far 2D)
→ higher-B → fibrils?
→ change material → cooling instabilities?