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Impact Pressure Shaping Plasma Jets and Affected by High-metallicity

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The high Mach number plasma jet have been extensively studied both astronomically and experimentally. Here, we reconstruct the magnetohydrodynamic (MHD) theory and propose a new analytical method to analyse the high Mach number plasma jets generated by intense laser interactions. Initially, we identify the determinants of local plasma density evolution through a reformulation of the fundamental MHD equations. Then, by MHD simulations on intense laser irradiating planar targets, the impact pressure plays a dominant role during the high Mach number plasma jet transmission. Moreover, a strong dependence on atomic number is identied and higher-Z materials amplify impact pressure, which imply high metallicity affects the structure of astronomical jets.

We firstly reformulate the compressive MHD equations as

$$\frac{\partial^2 \rho}{\partial^2 t} = \boldsymbol{\nabla\nabla} \cdot ((P_s + P_B)\boldsymbol{I} - \boldsymbol{T_\tau} + \boldsymbol{T_B} + \boldsymbol{T_{imp}}) \qquad (1)$$

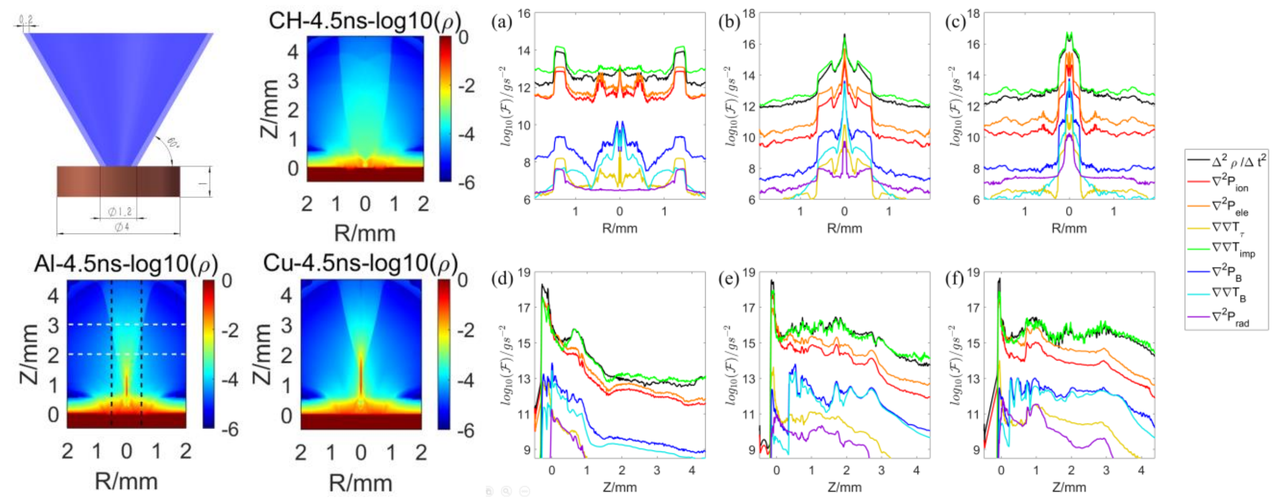
where ρ is the fluid density, $P_s = P_{ele} + P_{ion} + P_{rad} + \cdots$ is the total static pressure (including gravity), P_B is the magnetic pressure, T_τ is the viscous stress tensor, $T_B = -\frac{1}{4\pi}BB$ is the magnetic tension tensor, and T_{imp} is the impact pressure (also called dynamic pressure).

We perform numerical simulations using the FLASH MHD code, modeling the interaction of a ring-shaped laser pulse with a planar target composed of materials such as CH, Al, and Cu. The ring laser operates with a pulse width of 1*ns*, a wavelength of 351 *nm*, and a total energy output of 1 *kJ*. Simulation results show that the temperature is about 100 *eV*, the plasma velocity is approximately 600 *km/s*, the local sound speed is about 60 km/s, corresponding to Mach numbers exceeding 10, which indicates a supersonic jet.

Our results demonstrate that jet collimation improves with increasing atomic number of the target material. Furthermore, the impact pressure dominates the source term in the second-order density equation in both axial and radial directions. This leads to the conclusion that impact pressure plays a critical role in jet shaping, and that jet collimation is strongly influenced by the material's metallicity. The simulation results are consistent with recent laboratory experiments[1] and some astronomy jets with scaling law applied[2].

References

[1] L. Gao, E. Liang, Y. Lu, et al., Mega-gauss plasma jet creation using a ring of laser beams, The Astrophysical Journal Letters 873, L11 (2019)
[2] Komissarov, S.S., Ram-pressure confinement of extragalactic jets. Monthly Notices of the Royal Astronomical Society, 266, 649-652(1994)



Left: The configuration of simulation and the plasma density (g/cm3 in logarithmic form) of CH, Al and Cu target at 4.5 *ns*. Here, Region I is the region between the white dashed lines. Region II is the region between the black dashed lines. Right: Distribution of $\frac{\partial^2 \rho}{\partial^2 t}$ and its component in Eq.1 at 7.5ns. (a, b, c) the average of each factor along Z-direction for different materials in Region I. (d,e,f) the average of each factor along the R-direction for different materials in Region II. Regions I and II are indicated in Fig. 1. Here, (a, d) of CH target, (b, e) of Al target, (c, f) of Cu target