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Large-scale directional outflows of supersonic plasma, also known as ‘jets’, are ubiquitous phenomena in astrophysics [1]. The interaction of such jets with surrounding matter often results in spectacular bow shocks, and intense radiation from radio to gamma-ray wavelengths. The traditional approach to understanding such phenomena is through theoretical analysis and numerical simulations. However, such numerical simulations have limited resolution, often assume axial symmetry, do not include all relevant physical processes, and fail to scale correctly in Reynolds number and perhaps other key dimensionless parameters. Additionally, they are frequently not tested by comparison with laboratory

experiments. Recent advances in high-energy-density physics using large inertial-confinement-fusion devices now allow controlled laboratory experiments on macroscopic volumes of plasma of direct relevance relevant to astrophysics [2]. In this Letter we report the first results of experiments designed to study the evolution of supersonic plasma jets and the bow shocks they drive into a surrounding medium. Our experiments reveal both regular and highly complex flow patterns in the bow shock, thus opening a new window – complementary to computer simulations – into understanding the nature of three-dimensional astrophysical jets.

Extra-galactic jets emanate from the central regions of many active galactic nuclei [3,4]; jets are observed in star-forming regions [5,6,7] where they are associated with young stars and stellar objects; and it has been proposed that jets may play a crucial role in gamma-ray bursts [8], core-collapse supernovae [9], and the dynamics of supernova remnants [10]. Astrophysical jets carry prodigious amounts of energy and momentum and strongly influence the surrounding matter through which they propagate, be it extragalactic, interstellar, or circumstellar matter, or the matter of an exploding star. An important tool in enabling a greater understanding of the underlying physics of these jets has been numerical simulations. However, many obstacles to their use include the huge disparity of spatial and temporal scales involved in jet propagation and interaction with surrounding matter, and, in many cases, the necessity to account for such physical processes as radiation, relativistic fluid motion, and magnetic fields. Even when these latter processes are unimportant, source variability, the onset of turbulence due to various hydrodynamic instabilities, and interaction of the jet with non-uniformities in the surrounding medium make behaviour of the jet very complex and thus difficult to simulate.

A new window into the experimental study of astrophysical plasmas has recently been opened by the advent of high-energy-density (HED) drivers associated with inertial-confinement-fusion studies [11]. The ability of HED machines to create macroscopic volumes of plasma with extreme properties has already been used to explore the behaviour of supernova blast waves [12] and massive planet cores [13]. HED laboratory-astrophysics studies of jets have also shown promise, but until now have been confined to systems which either do not study the fundamental nature of the jet's interaction with its surrounding medium [14,15], or, if an ambient medium is present, are constrained to such short time scales that turbulent hydrodynamics does not develop [16]. Our present work responds to these important limitations. In this Letter, we report the first results of experiments designed to explore the late-time evolution of collimated, dense-plasma jets and the complex, three-dimensionally-structured bow shocks they create.

Our experiments have been carried out at the Omega laser facility [17] of the University of Rochester, using the configuration shown schematically in Figure 1. The laser target consists of a titanium foil (with a thin plastic coating) in direct contact with a titanium 'washer'. The Omega laser heats this foil, launching a near-planar, ablatively driven shock into the titanium. The shock exits the foil after the laser pulse ends, and expansion cooling creates a directed outflow of heated titanium down the cylindrical hole in the washer. Upon exit from the hole, this material may be characterised by its internal Mach number, $M = u/c$, where u is the outflow velocity and c is the sound speed in the outflowing material. We are able to achieve a supersonic outflow with $M \sim 2 - 5$. The resulting well-collimated supersonic jet then enters a block of low-density polymer foam, with which it interacts. Following the formation of this primary jet, the shock within the titanium target continues to progress along the sides of the hole, resulting in the inward collapse of the hole and the formation of a secondary jet of material by a process analogous to that occurring in an explosive 'shaped charge'. This secondary jet interacts with the high-pressure cocoon surrounding the primary jet within the foam. Formation of both jets is a purely hydrodynamic phenomenon; it does not rely upon radiation energy loss or magnetic fields.

We diagnose the density distribution within the titanium jet, and the bow shock in the surrounding medium, by point-projection x-ray radiography [18] using a laser-heated vanadium plasma as the x-ray backlighting source. This x-ray backlighting source is apertured by a 20-µm diameter pinhole, enabling a shadow image of the jet and its associated shocks to be projected onto x-ray film with high resolution. The radiographic data (Figure 2) clearly show an initially well-collimated jet that becomes increasingly structured as time progresses, and the development of much detailed structure at the bow shock. Structure in the bow shock is strongly reminiscent of that observed in images of astrophysical objects such Herbig-Haro jets [5].

An extensive series of calculations for the design and interpretation of these experiments is being carried out using a combination of the radiation-hydrodynamics and pure-hydrodynamics codes LASNEX [19], RAGE [20], NYM [21], PETRA [22], TURMOIL3D [23], HYADES [24] and ALLA [25]. The Lagrangian LASNEX, NYM and HYADES hydrocodes are used to treat the early-time interaction between the incident laser energy and the titanium target. The properties of specific simulations vary, but in some cases include laser ray-trace and non-local thermodynamic equilibrium (NLTE) energy-deposition physics, and the absorption of laser energy by inverse bremsstrahlung in the coronal plasma. NLTE physics in the laser-absorption region is treated in the time-dependent, screened-hydrogenic approximation. Elsewhere tabular LTE opacities are used for the calculation of radiation transport, although ion, electron and radiation temperatures are separately resolved in all cases. Equation-of-state data are used in tabular form. After ~ 2 ns, no further input of energy from the incident laser beam takes place, and the evolution of the jet and its interaction with the surrounding medium involves a highly non-uniform flow with a high degree of material deformation. To treat this type of flow, calculations are transferred to the Eulerian RAGE, PETRA or ALLA hydrocodes, and the subsequent jet formation and evolution are tracked in the Eulerian phase of the simulations. Radiation transport in RAGE and PETRA are treated by single-group (grey) diffusion whereas ALLA does not include any treatment of radiation. Figure 2 shows the comparison of the experimental data with synthetic radiographs from NYM-PETRA and RAGE simulations of the experiment. The development of the primary jet following outflow of shock-heated titanium is evident at early time (100ns). At later time, this primary jet evolves into a complex, three-dimensional structure (and associated bow shock), visible at the head of the jet. The dense, collimated, secondary jet is clearly evident in both experiment and simulation at late time.

Typical conditions found in simulations of the experiment for regions near the head of the jet and at $t = 300$ ns are: temperature, $T = 3$ eV; density, $\rho_{jet} = 0.1$ g cm^{-3}; density scale length, $r = 4 \times 10^{-3}$ cm; and fluid velocity, $u = 1 \times 10^{6}$ cm s^{-1}. We infer that the primary jet is a weakly ionized gas, and that the local sound speed, c, within the jet is 4×10^{5} cm s^{-1}, corresponding to an internal Mach number, M ($= u/c$) of ~ 3. The jet-to-ambient density ratio, $\rho_{jet} / \rho_{ambient}$, is ~ 1. The secondary jet is characterised by lower internal energy density than the primary jet, and in the present experiments is close to the liquid state. With the larger energy densities soon to be available at the National Ignition Facility (NIF) [26], it will be possible to obtain a high Mach-number, gas-like secondary jet.

To extend our experimental system to the astrophysical context, we must scale it to an appropriate astrophysical environment. Such scaling has been studied in detail by Ryutov *et al*. [27], who show that if dissipative processes are negligible, then scaling transformations exist that enable the hydrodynamic evolution of the laboratory system to be mapped onto that of a system at vastly different physical size. However, this scaling is only meaningful if dissipative processes (such as viscous damping and thermal conduction) may be neglected. We characterize their importance through the Reynolds and Peclet numbers, Re = ur/ν, and Pe = ur/κ, where ν and κ are, respectively, the kinematic viscosity and thermal diffusivity. Using Spitzer's [28] expressions for ν and κ, we infer Re ~ 10^6 and Pe ~ 10^3, both very much greater than one. Viscous drag and thermal conduction are thus negligible in comparison with inertial forces and the advection of kinetic energy under the conditions of our experiment. In most astrophysical settings Re and Pe are also extremely large. Moreover, the Reynolds number in our experiments exceeds that expected for the transition to turbulence [29], and we observe as expected the development of highly-complex, three-dimensional flow in the interaction of jet and bow shock after sufficient elapse of time. This complex fluid motion prevents the simulations from matching the details in the head of the jet.

When radiation transport, relativistic and magneto-hydrodynamic effects can be ignored in the astrophysical setting, scaling between our experimental system and corresponding astrophysical systems should depend only on the internal Mach number, M, of the jet and the jet/ambient density contrast, $\rho_{jet}/\rho_{ambient}$. Jets from young stellar objects (YSOs) tend to have high values of M ~ 20 – 100, and $\rho_{jet}/\rho_{ambient}$, significantly larger than one. YSO flows are further complicated by radiation cooling behind the shock front. Large-scale extragalactic jets tend to produce lower-Mach-number, low-density-ratio jets, and our current experiments may thus be of closest relevance to extragalactic flows. Future experiments using NIF may allow experiments to reach higher Mach numbers, and cooling regimes appropriate to YSO jets.

The experimental setting may also be relevant to jets and collimated outflows in core collapse supernovae and supernova remnants. The nature and characteristics of directed outflows generated in the process of a stellar core collapsing into a neutron star or a black hole is now a subject of active debate [26,27]. Many observable characteristics of supernova explosions, such as polarization and the chemical composition of ejecta, as well as the morphology of resulting supernova remnants should depend on the velocity and density of a directed outflow caused by core collapse.

Our experiments are the first high-energy-density laboratory experiments to image the complex, turbulent flow in dense-plasma jets and their corresponding 3-dimensional bow shocks. We believe that such experiments provide a unique opportunity for better understanding of analogous astrophysical jets, and will extend understanding outside the limits imposed by current hydrodynamic modeling where the necessary spatial resolution for hi-fidelity simulation will be unattainable for years to come.

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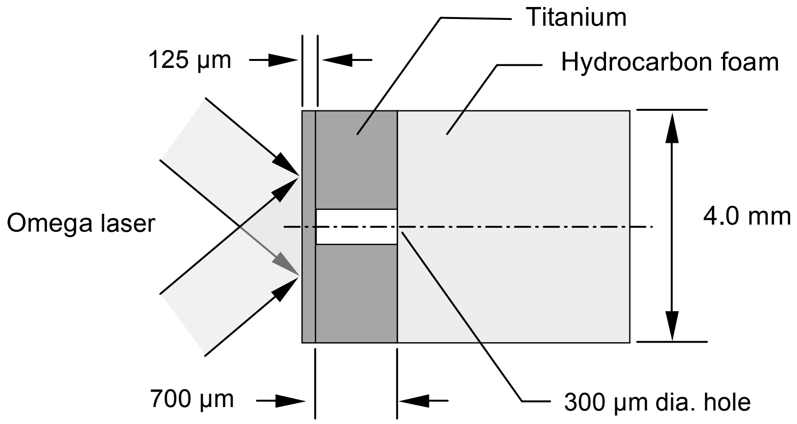
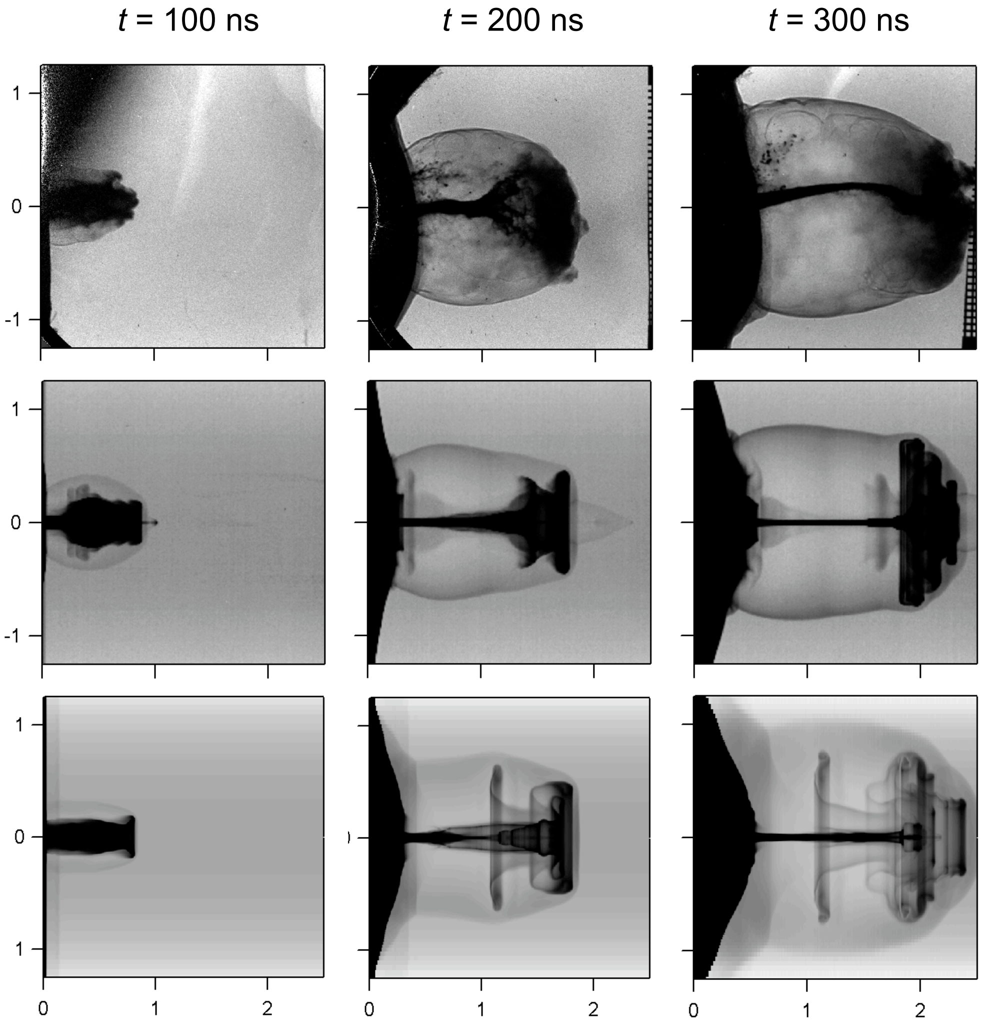
Figure legends

Figure 1. Experimental arrangement for the laser-driven supersonic-jet experiment. The laser target consists of a 4-mm diameter, 125-μm thickness titanium disc, in contact with a 700-μm thickness titanium 'washer' with a central, cylindrical hole of 300-μm diameter. The face of the disc is illuminated by seven beams of the Omega laser, focused into a spot size of 0.6-mm diameter (50 % intensity point). Laser pulse duration is 1 ns, with incident intensity of 5×10^{14} W cm^{-2}; the incident intensity distribution is smoothed by random phase plates. Shock transit through this assembly results in the formation of a supersonic, dense-plasma jet that propagates into an adjacent cylindrical block of low-density, resorcinol-formaldehyde ($C_{15}H_{12}O_4$) foam. This foam material has a density of 0.1 g cm^{-3}, and is chosen because of its small cell size of less than 0.1 μm. The interaction between the jet and the surrounding foam medium is diagnosed by point-projection radiography, using a 5.20 keV (He-like vanadium) x-ray backlighting source.

Figure 2. Experimental (top) and simulated (middle, using the RAGE hydrocode; bottom, using NYM-PETRA) radiographs of the primary (evident at 100 ns) and secondary (smaller diameter, evident at 200 ns and later) titanium jets. The dome-shaped pedestal results from shock transit through the titanium/foam interface. The diameters of the pedestal and jets, and the diameter of the bow shock in the low-density foam surrounding the jet, are reasonably well modelled by simulation. The 2-dimensional simulations show a mushroom-shaped, Kelvin-Helmholtz roll-up at the head of the primary jet that does not reproduce well the complex, three-dimensional structure evident in experiment. Times shown are after the onset of the laser drive, and the units of distance are mm.


Titanium
125 μm
Hydrocarbon foam
Omega laser
4.0 mm
700 μm
300 μm dia. hole

[FIGURE 1]



[FIGURE 2]