Astrophysical jet experiments with laser-produced plasmas

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Introduction

Some of the most inspiring images in science are of astrophysical objects, and the study of the phenomena responsible for such images has long been of interest. The inventions of CCD technology, and the increased capabilities of telescopes, have allowed the harvesting of a huge amount of high-quality observational data, from which our understanding of the universe has traditionally been derived. These data allow the formulation of theoretical models, both phenomenological and empirical, describing the behaviour of objects ranging from our own planet, to supernovae, to black holes.

Observational data have limitations however: the time scale over which they are made is usually very short compared to the lifetime of the astrophysical object, and observation alone does not allow the thorough testing of models. Often we wish to build a more complete picture of the system, in order to understand how it has arrived at its current state, and how it might evolve in the future; or to examine the accuracy of the models in a variety of situations, and their sensitivity to initial conditions or perturbations.

To this end, numerical simulations play a key part in the understanding of these phenomena. Computer codes allow the extrapolation from a set of known physical quantities, extracted from observations, to a more complete description of the astrophysical system in question. This approach has proven hugely successful; however, many of the problems we wish to solve are highly non-linear, and of a multi-scale nature, both in space and in time. Thus, a full numerical simulation of their formation and evolution is beyond the capability of current computers. The ability to perform experimental simulations in a controlled laboratory setting therefore presents potentially huge advantages.

With use of technologies such as, for example, high-intensity lasers, or wire-array z-pinches, the production of energy densities of magnitudes only previously seen in astrophysical phenomena is now possible. This allows us to perform laboratory experiments that, if correctly designed and interpreted, can provide valuable insight into some of the outstanding problems in astrophysics. Thus, through the combined efforts of observation, numerical simulation, and laboratory experiments, we can hope to gain a fuller understanding of our universe.

The goal of these experiments is the development of astrophysically relevant experiments designed to provide insight into the physics of YSO jets. The question then naturally arises: to what extent can laser-plasma experiments - which last a few ns and have a spatial scale of at most a few mm - be relevant to the evolution of objects which are a few pcs is size, and last for 1,000s of years?

The approach is based on the scaling transformations identified by Connor and Taylor [1] and discussed in detail by Ryutov *et al*. [2]. Which states that it is possible to map laboratory experiments onto astrophysical scales - in a rigorous sense - provided that the two systems are described by the ideal MHD. It is always the case, however, that the two systems of interest are not ideal. Here, a less thorough approach may be taken, in which a set of criteria are identified that allow progress to be made toward a scaled experiment. In this thesis the approach of, for example, Lebedev *et al*. [3] is taken: if the two systems can be described hydrodynamically, and viscosity and heat conduction are negligible, then scaling is possible.

The applicability of the scaling relations is then characterised by three conditions: Reynolds number, Re, Péclet number, Pe and the collisionality greatly exceed unity and ζ is much smaller than unity. Where ζ is defined as the ratio of the ion-ion mean-free-path to jet radius. If these criteria are met, then three dimensionless numbers measure the similarity of any set of jets, for example the similarity between the laboratory experiment and the astrophysical jet.

The first is the internal Mach number, M, defined as the ratio of the jet flow velocity to the sound speed within the jet. Second, the density ratio, η, the ratio of the jet number density to the ambient number density. Third, the cooling parameter, χ, which is a measure of the importance of radiative cooling on the jet dynamics. This is given by the ratio of a characteristic cooling length for the jet to the jet radius.

Target

The targets design needs to satisfy a number of criteria so that it should produce plasma jets that may be scalable to Young Stellar Object (YSO) jets. In order to do this, laser irradiation of the target should result in a high-velocity, low-density plasma. Furthermore, the design must isolate the laser beams from the propagating jet, allowing the introduction of an ambient medium in to this region. In addition to this, the targets have been designed to allow good diagnostic access to the outflow region.

The simplest target design to satisfy these criteria is a v-foil design as shown in Figure 1. Two thin foils are placed at an angle to the central axis. The laser is incident from the outside of the 'v', with a separation between the focal spots. The plasma of interest then expands away from the rear side of the foils, in a direction normal to the target surface.

As the plasmas meet at the central axis, there is a stagnation of the flows in the direction perpendicular to the axis, which results in heating. The axial component of the momentum is conserved, and the result is a bulk flow along the central axis, moving away from the collision region.

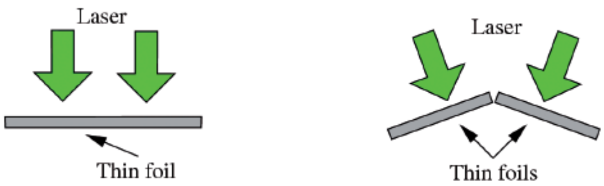

Figure 1. Schematic of the target design and laser beam geometry. Experiments compared the plasma outflow from the rear face of a planar target (left) to two angled planar targets (right).

This design allows a large number of variables to be changed easily - foil material and thickness, angle between the foils, and the separation between the two focal spots - in order to find the optimum condition for jet production. It is also possible to change the laser pulse characteristics: focal spot size, energy, pulse length and wavelength. These parameters are confined somewhat by the capability of the laser system and by simulation.

Simulation indicate that a 1 ns duration, frequency doubled beam of Vulcan irradiating an 0.8 µm foil produces a rear face plasma expansion 1.5×10^8 cm s^{-1} (1500 km s^{-1}) and at 2 ns has reached a distance of around 1.5 mm from the original target. Both the electron and mass density at this point are approaching a value that is expected to produce a scalable jet, while the particle temperatures are around 200 eV.

The choice of angular separation between the foils should be large enough to ensure that a significant component of the plasma velocity is in the axial (jet propagation) direction, and the collision between the two plasmas should act to collimate the plasma outflow. The first condition requires that the angle be greater than 90º, while the second condition suggests that the angle cannot become too great, that is, it should be less than 180º. For these reasons, a value of 140º was chosen. An optimum laser spot separation, of 0.80 mm, was found by experiment.

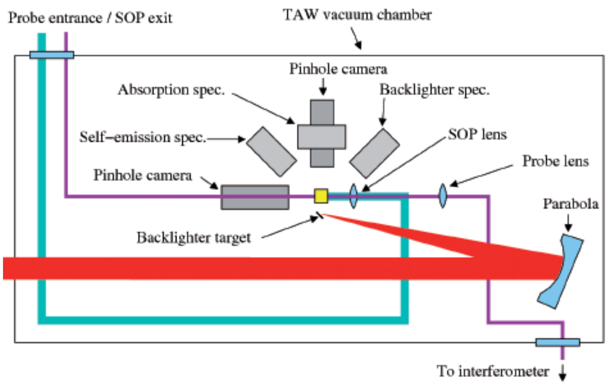

Figure 2. This shows a plan view of the TAW vacuum chamber and the diagnostic layout. The jet propagation direction is into the page. The principal diagnostic is the optical probe is shown in purple, the SOP is shown in blue.

Experiment

Two Vulcan these beams were used, with one beam for each v-foil target, see Figure 3. The beams were focused with f/10 lenses, and entered from the top of the chamber at an angle of 40º to vertical. This beam arrangement resulted in a jet propagating in the downward direction. Two diagnostic beams - for the optical probe and an X-ray backlighter - entered the chamber in the horizontal plane. The diagnostics were arranged in the horizontal plane around the target, with the exception of the collection lens for the streaked optical pyrometer (SOP) and the gated optical imager (GOI), which was placed below the target, to image the jet in end-on geometry.

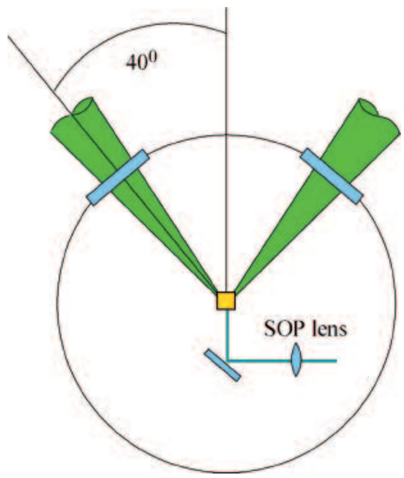

Figure 3. This shows the north-south (left) and east-west (right) view of the TAW vacuum chamber, the geometry of the drive beams and the SOP diagnostic.

The optical probe was frequency converted to 4ω (264 nm) and ran as a Normarski interferometer. This was used to infer the electron density. The minimum electron density-path length product, determined by the probe wavelength and the smallest resolvable fringe shift, was 2×10^{17} cm^{-3} mm. The SOP was used to give an indication of the plasma temperature, this was determined from the plasma self emission imaged at 400 nm onto a streak camera (the SOP) and a GOI through a calibrated optical system.

For some measurements the chamber was back-filled with a known pressure of nitrogen. In shots were this was used, the chamber was first evacuated to a level < 10^{-1} mbar before the introduction of the gas.

Results

Only the interferometric data will be described. These measurements were used to determine the plasma expansion speed and jet shape and infer the electron density. Data from 0.8 µm thick aluminium planar targets shot with a single beam indicates that high expansion velocity, $4 \pm 0.1 \times 10^7$ cm s^{-1} (400 ± 10 km s^{-1}), plasma expansion occurs at the rear face of the target.

A second series of measurements were taken from planar targets irradiated with two beams with focal spot separation of 1 mm. Measurements taken at 10 ns delay relative to the drive beams are shown in Figure 4. These measurements show a series of small scale features in the collision region between the two foils. In this region the interference fringes are indistinguishable. The extracted phase maps show that further from the target surface, the central axis is characterised by a region of higher phase shift, indicating high plasma density.

A third set of results were taken using v-foil targets. Data and the extracted phase map, taken at 10 ns, is shown in Figure 4. An enhanced phase shift is observed along the central axis; this enhancement is more prominent than with the planar targets. The high-density region extends beyond 3 mm, further than the planar targets. For these targets the region of indistinguishable fringes is again seen.

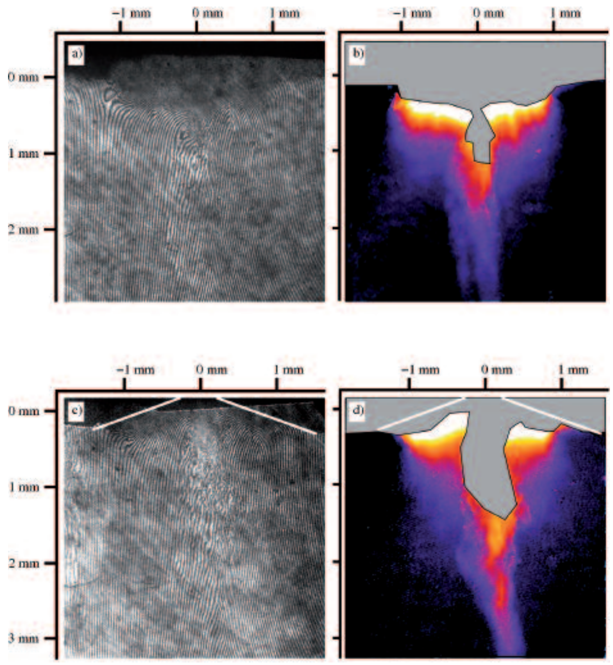

Figure 4. Interferograms (left) and extracted phase maps (right) from a plane foil (top) and a v-foil (bottom) taken 10 ns after the drive lasers. In the collision region the fringes are scrambled and the phase cannot be extracted. Where data is not available the phase map is shown as grey.

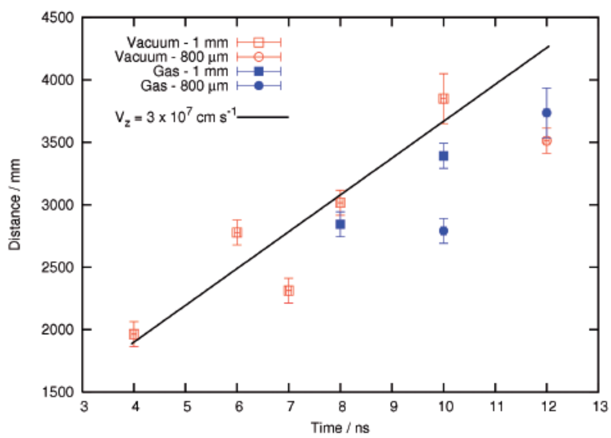

Figure 5. The plasma extent in the axial direction. Data from four different types of shot are shown, all with foils of thickness 0.8 µm: both with and without ambient gas, for focal spot separations of 1 mm and 800 µm. The straight line shows a least squares fit to the data in vacuum, with a separation of 1 mm, and gives V = 3 ± 0.8 × 10^7 cm s^{-1} (300 ± 80 km s^{-1}).

The velocity of the plasma outflow for the v-foil targets, after the plasmas have collided, was determined from a series of shots taken with probe delays between 4 ns and 12 ns. The extent of the plasma was defined as the furthest point from the original target position where a phase shift could be measured. The results are plotted in Figure 5. Four different sets of experimental conditions were used. These are shots in vacuum, with a focal spot separation of 1 mm (red open squares); in vacuum with a focal spot separation of 0.8 mm (red open circles); in 5 mbar nitrogen gas, with a focal spot separation of 1 mm (blue closed squares); and finally, in 5 mbar nitrogen gas, with a focal spot separation of 0.8 mm (blue closed circles). The majority of the data points are for shots with a spot separation of 1 mm, taken in vacuum. A least squares fit to these data points yields a velocity of $3\pm0.8\times10^7$ cm s^{-1} (300 ± 80 km s^{-1}).

By assuming a constant electron density along the probe path, a chord averaged value can be inferred from the phase shift maps. In order do this, the length of plasma traversed by the probe beam was estimated by taking measurements of the plasma extent with the v-foil target rotated through 90°.

There were no direct measurements of temperature or ionisation for the experiment. The absence of K-shell emission from the jet region, limits the plasma temperature is less than ~100 eV. Previous measurements taken at the LULI laboratory suggests that the plasma outflow temperature was 10 eV. This value was used to estimate the plasma ionisation.

Scaling

The relevance of these experiments to astrophysical systems can be determined by a series of dimensionless parameters derived from scaling arguments. In order to be able to apply these relations, the plasma must behave as an ideal fluid: it should Re and Pe >> 1, while the plasma particles must be localised on a scale length less than the size of the system, such that ζ << 1.

	Experiment	YSO jet
Reynolds number, Re	$10^5 - 10^7$	10^7
Péclet number, Pe	$10^2 - 10^3$	10^6
Collisionality, ζ	$10^{-8} - 10^{-6}$	10^{-6}
Density contrast, η	10 – 50	1 – 20
Mach number, M	20 – 40	20 – 40
Radiative cooling, χ	0.1 – 1	0.1 – 10

Table 1. Inferred dimensionless parameters from the experiment compared with those typical of a YSO jet.

Assuming that the above strong inequalities are satisfied, the similarity of the laboratory and astrophysical jets can be described by three dimensionless parameters: η, M, and χ. These parameters should be matched between the two systems for a successfully scaled experiment. In order to evaluate these parameters, characteristic values of the plasma outflow flow speed, diameter, electron density, electron temperature and ionisation were inferred from experiment.

The inferred values of Re, Pe and ζ satisfy the necessary conditions for the scaling laws to be applied. Evaluating the density contrast, Mach number and cooling parameter for these targets, we see that there is substantial overlap between the laboratory and YSO jets. A cooling parameter of less than unity means that radiative cooling is dynamically important for the system, while $\chi > 1$ results in an adiabatic expansion; the laboratory jets are therefore in a transitional regime between a radiative and an adiabatic flow.

Conclusion

Probe results of the v-foils from the TAW experiment indicate that the collision of the two foils results in a narrow plasma outflow, moving at ~3×10^7 cm s^{-1} (300 km s^{-1}), provided that the foils are sufficiently thin. These outflows are visible at times of > 12 ns after the arrival of the drive beams. When an ambient gas of 5 mbar nitrogen is introduced into the vacuum chamber, the width of the jet is reduced, and shock structures are seen to form at the leading edge of the jet. This is consistent with previous computational work, and indicates that the interstellar medium may play an important role in the collimation of YSO jets. The inferred dimensionless scaling parameters suggest that the jets in the experiment are in a regime where they could be relevant to YSO jets. It is noted, however, that the constraint of geometric similarity between the two systems would need to be addressed in any future experiment, through use of a cylindrically symmetric target design. The optimum target might then be a cone of apex angle 140º, with the laser beams arranged in an annular pattern on its outer surface. This kind of target would provide cylindrically symmetric inertial confinement of the outflow, resulting in a higher temperature on axis. This, in turn, should increase the degree of radiative cooling, and move the jets into the radiative regime. In addition, the higher-density of material will result in jets that last for longer times, when compared with the current design, allowing hydrodynamic effects more time to develop.

Finally, we note that the v-foil target design allows the foil materials to be varied, to examine the effects of radiative cooling. The introduction of a magnetic field into the jet propagation region is also possible. The importance of these factors on jet collimation and propagation will then be the aim of future experiments.

Acknowledgements

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