

Astrophysical Jets with Conical Wire Arrays: Radiative Cooling, Rotation & Deflection

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Abstract. Highly collimated outflows or jets are produced by a number of astrophysical objects including protostars. The morphology and collimation of these jets is thought to be strongly influenced by the effects of radiative cooling, angular momentum and the interstellar medium surrounding the jet. Astrophysically relevant experiments are performed with conical wire array z-pinches investigating each of these effects. It is possible in each case to enter the appropriate parameter regime, leading the way towards future experiments where these different techniques can be more fully combined.

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WIRE ARRAY Z-PINCHES FOR LABORATORY ASTROPHYSICS

Wire array z-pinches are an extremely versatile tool. Most applications of wire array z-pinches have been concerned with the emission properties as the wire array stagnates, either as an extremely intense and efficient soft x-ray source which can then be applied to Inertial Confinement Fusion, High Energy Physics applications, or alternatively utilizing the strong K-shell line emission from low- to mid-Z elements. A growing application of wire array z-pinches is their utility in performing astrophysically relevant experiments [1]. Again some of these use the z-pinch purely as a radiation source for either radiation driven jets, or as radiation source and source for absorption spectroscopy and photo-ionization experiments. Alternatively the plasma structure and evolution of a wire array z-pinch can be used to model astrophysical objects.

Prior to the final stagnation on to the array axis a wire array z-pinch implosion undergoes an ablation phase, where precursor material is streamed to the array axis. This precursor flow exhibits many characteristics which are relevant to specific astrophysical scenarios, particularly super-Alfvénic and/or super-sonic flows, significant radiative cooling, high plasma Beta and fully collisional flows. However to be of use to the astrophysical community it is critical that the plasma flow structure and evolution be engineered in order to represent astrophysical objects. The ablation

stage of a wire array z-pinch is particularly appropriate for this as the flow of the precursor streams is easily predicted by the initial current and magnetic field structure. This precursor phase of a wire array z-pinch also exhibits another key criteria for modeling certain astrophysical objects – it is quasi-steady state, i.e. the system is static on characteristic time scales, typically taken to be the time taken for a shock to cross an object, such as the precursor column.

Protostellar jets are an object currently of interest to the astrophysical community. There is particular interest in the formation mechanism, internal structure, curvature of the jet, the final bow shock at the head of the jet, as well as the effects of rotation and radiative cooling on the jets. Each of these effects has been observed and simulations have been performed to investigate the physical mechanisms associated with each of these features, however simulations are limited by resolution and physical process incorporated. Here we discuss laboratory experiments specifically designed to bring insight into these specific processes stellar jets.

JET FORMATION & THE EFFECT OF RADIATIVE COOLING

A conical wire array [2] consists of a set of fine (tens of μm diameter) metallic wires, that are each inclined with respect to the vertical axis, creating a conical arrangement. As current passes through the wires the wire cores remain relatively cold whilst a hotter coronal plasma forms. The lower resistivity within this coronal region leads to a concentration of current and hence the $\mathbf{J} \times \mathbf{B}$ force leads to a continuous streaming of this plasma to the axis. Continuous ablation of the core replenishes this material. In contrast to cylindrical arrays, for the conical array a radial component to the current (J_r) is present, hence the Lorentz $\mathbf{J} \times \mathbf{B}$ force on the corona has an axial component ($F_z = J_r \times B_\phi$). As the flows meet on the axis the radial component of the momentum from all of the streams cancels and the kinetic energy associated with this momentum is thermalized in a conical shock. Radiative cooling limits the thermal expansion of the streams and plasma column. The axial component of momentum from the streams is conserved, producing an axial outflow or jet. This flow is additionally accelerated by a steep pressure gradient at the top of the conical shock, producing a jet of plasma.

Figure 1a-c shows schlieren images from a single experiment with a W jet at three different times. In the first image (at 308ns) a long narrow column of plasma is seen. The diameter decreases towards the jet tip. The tip of the jet, which is 9.4mm from the anode, has a diameter of $175\mu\text{m}$ whilst the diameter nearer to the anode plate is $560\mu\text{m}$. The 3-frame laser shadowgraphy system shows that the plasma is propagating upwards, away from the conical shock. The positions, with associated error margins are plotted on Fig 3.14d. The gradient of the graph indicates that for this experiment the axial velocity of the jet tip is $275 \pm 13 \text{ km/s}$. The jet in Fig 1a is extremely well collimated, with a radial expansion velocity of less than 2% of the axial velocity. This velocity ratio is consistent with a Mach number ≥ 30 . This expansion rate can be controllably increased (i.e. deteriorating the jet collimation) either by increasing the jet temperature or by increasing the angular momentum in the jet.

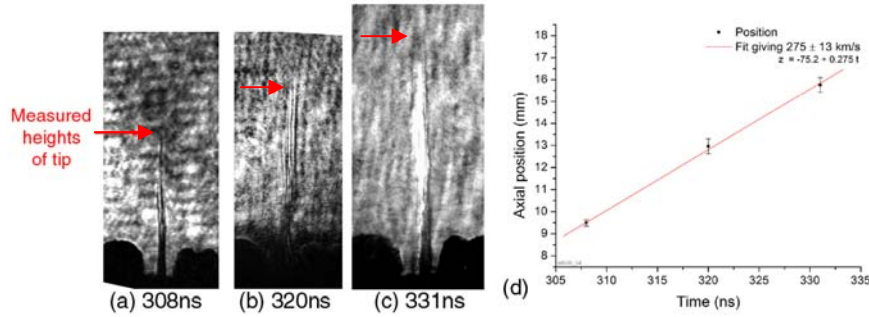


FIGURE 1. Schlieren images of a jet produced by a W conical array at (a) 308ns, (b) 320ns and (c) 331ns after start of current (all from the same experiment and on the same scale). (d) is a plot of the tip positions from each of these images. The red lines on the images (a,b,c) correspond to the measured heights of the tip plotted on the graph (d).

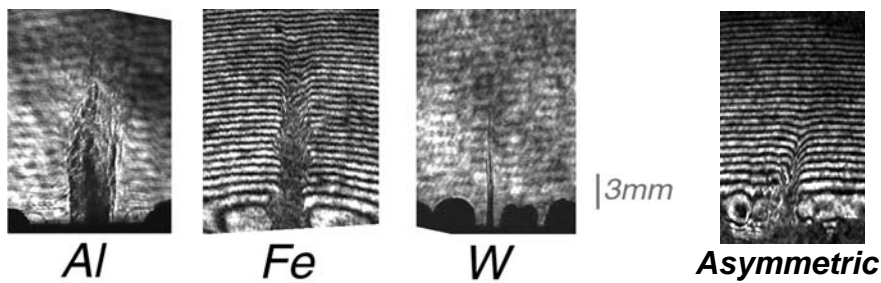


FIGURE 2. Schlieren/interferometer images of jets from arrays of different materials: Aluminum (left), Stainless steel (interferometer, centre) and Tungsten (right). All images are taken at times $t \sim 300 - 320$ ns after the start of current. A jet produced by a W array with 2 out of the 16 wires removed is also shown.

Given that there is negligible angular momentum in the jet in Fig 1, the tight collimation of this jet is the result of low thermal expansion due to the high rate of radiative cooling of tungsten. To vary the cooling length of the jet the array material can be changed; for the typical temperatures and densities of the jet the radiative cooling rate increases with increasing atomic number [2]. Figure 2 shows jets from three materials - aluminum ($Z=13$), stainless steel (iron, $Z=26$) and tungsten ($Z=74$). A significant difference is also seen in the morphology of each jet - the W jet is a well defined column of plasma, whereas the Al jet is more disrupted. The most significant effects of cooling can be seen on the diameter of the conical shock and the collimation of the jet – thermal expansion is greater for Al, so the opening angle of the jet is larger ($\sim 12^\circ$) compared to the W jet ($< 2^\circ$).

This experiment can be adapted to demonstrate the effect of asymmetry on jet production in a conical shock. Fig 2d shows a jet produced by an identical array as Fig 2c, except that two consecutive wires have been removed to lead to an asymmetry in the flow onto the axis. It is seen that, while there is a change in the jet direction, the jet remains collimated despite a serious perturbation into the symmetry in the formation region.

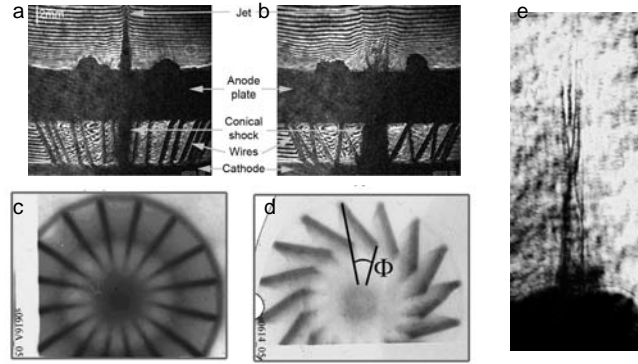


FIGURE 3. Side on laser interferometry images of untwisted and twisted conical arrays and end on self-emission imaging at 30eV. A laser schlieren image of a rotating jet is also shown.

EFFECT OF ANGULAR MOMENTUM

Instead of increasing the jet temperature, and hence decreasing the jet Mach number, we can investigate the effects of introducing angular momentum into the jet [3,4]. Figure 3 shows an overview of an experiment to study the introduction of angular momentum. In Fig 3a is a setup similar to Fig 1, however in Fig 3b the conical array has been twisted, with the anode rotated $2\pi/16$ radians with respect to the cathode. This twist manipulates the magnetic field structure in the array, hence introducing an azimuthal component to the $J \times B$ force.

In Fig 3b we see that the jet is significantly more divergent than Fig 3a, and that both the conical shock and jet have increased in size. This change in size is diagnosed well by imaging in XUV and soft x-ray emission down the axis of the system, as shown in Fig 3d. The shock on the central axis of the array steadily increases as the level of angular momentum in the system is increased. A simple analytic model has been developed [3] to estimate the rotation rate of the column, and to determine the initial angular momentum in the streams as they are ablated from the wires. Both the model and MHD simulations show close agreement with the experimental data.

JET DEFLECTION

Another effect that is thought to have a significant impact on jet collimation is the pressure on the jet material due to the ambient medium – the interstellar medium for protostellar jets. There are many different configurations of ambient medium that jets might propagate through, including a relatively uniform ambient medium, and one that has a motion transverse to the direction of jet propagation. Conical wire array z-pinches have been used to model both of these scenarios. For the static ambient medium case, a bow shock is formed at the jet tip, and in some cases multiple bow shocks are observed (see [5] for details of this experimental setup, and results). The case with a transverse wind has been modeled using a photo-ablated CH foil; material is ablated perpendicular to the foil [6,7]. Figure 5 shows data from this type of experiment. The main body of the jet is deflected by the wind. Many shocks are seen within the jet, which are thought to fall into various subsets – internal oblique shocks

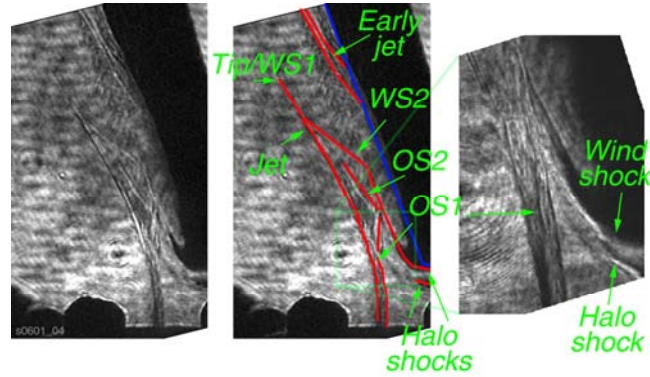


FIGURE 5. Side on laser schlieren images of a jet propagating in a transverse wind. The wind is produced by ablating a CH foil.

(OS) which are responsible to redirecting the jet flow, working surfaces (WS) which are formed at the jet-wind boundary and the jet attempts to tunnel through the ambient medium (these and other shocks are discussed in more detail in [7]). Recently these experiments have been used to benchmark codes used to model astrophysical jets [8, 9].

SUMMARY

Experimental techniques have been developed that allow the jets produced by conical wire arrays to cover much of the parameter space occupied by their stellar equivalents. Table 1 summarizes many of the dimensionless parameters that describe both YSO and the laboratory jets (also including some of the general flow parameters which are used to derive these). In the table it is seen that laboratory experiments can reach the correct degrees of cooling, density contrast, length to radius aspect ratio, rotations and wind pressures that represent stellar jets.

A number of experimental configurations where conical wire array z-pinchs are used to study effects on astrophysical jets are discussed. Jets which have a low internal energy and do not contain significant angular momentum are seen to be exceptionally well collimated. The effects of increasing internal energy and angular momentum are seen in experiments where the wire array, and hence jet material is change and where the array is twisted respectively. Both of these are seen to have a detrimental effect on jet collimation. Experiments have also been performed where the jet propagates through an ambient medium that is either static or has a transverse motion. In the former case one or more bow shocks are formed at the jet-cloud boundary, and in the latter the jet is deflected by the presence of the wind, with the formation of shocks in both the jet and the wind.

Work continues in better matching the full boundary conditions of these jets, and more importantly investigating how combining these characteristics deepens our understanding of astrophysical jets. For example recent studies have numerically studied how the deflection of a jet by a side wind is effected by rotation in the jet [*]. Such experiments are planned in the future.

TABLE 1. Dimensional and Dimensionless parameters relating our laboratory jets to those from Young Stellar Objects [2]. Experimental dimensionless parameters shown in bold are the ranges of values achievable by variations to the experiment configuration, as described in the text; however this is not necessarily a control independent of other parameters.

Parameter	YSO jet (away from source)	Conical wire array Z-pinch jet
General flow variables		
Length (cm)	3×10^{17}	2
Radius (cm)	2×10^{16}	0.1
Dynamical time scale	10^3 years	100ns
Electron temperature (eV)	1	10
Jet tip velocity (km/s)	~ 100	~ 200
Jet bulk velocity (km/s)	~ 100	~ 100
Azimuthal (rotation) velocity (km/s)	0 – 10	0-20
Jet Density (g/cm^3)	$\sim 10^{-22}$	10^{-4}
Validity of fluid description [2]		
Localization parameter (mfp/r)	$\ll 10^{-6}$	$\leq 10^{-4}$
Reynolds Number (Re)	$> 10^8$	10^5
Peclet number (Pe)	10^7	$2 - 2 \times 10^3$
Jet scaling parameters in 1D		
Mach number, M	> 10	10-30
Density Contrast, η [5,6]	1 – 2	$\sim 1 - > 10^3$
Cooling parameter, χ [2]	0.1 – 10	5-10
Jet aspect ratio (Length/Radius)	> 15	3-20
Parameters representing 3D effects		
Rotation fraction (v_ϕ/v_z) [3]	0 – 0.1	0 – 0.2
Wind velocity contrast [6]	0 – 0.2	0 – 0.5

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