Laboratory astrophysics experiments studying hydrodynamic and magnetically-driven plasma jets

F Suzuki-Vidal\textsuperscript{1}, S V Lebedev\textsuperscript{1}, M Krishnan\textsuperscript{2}, M Bocchi\textsuperscript{1}, J Skidmore\textsuperscript{1}, A J Harvey-Thompson\textsuperscript{1,5}, G Burdiak\textsuperscript{1}, P de Grouchy\textsuperscript{1}, L Pickworth\textsuperscript{1}, L Suttle\textsuperscript{1}, S N Bland\textsuperscript{1}, J P Chittenden\textsuperscript{1}, G N Hall\textsuperscript{1}, E Khoory\textsuperscript{1}, K Wilson-Elliot\textsuperscript{2}, R E Madden\textsuperscript{1}, A Ciardi\textsuperscript{3} and A Frank\textsuperscript{4}

\textsuperscript{1} Department of Physics, Imperial College London, Prince Consort Road, London SW7 2BW, UK
\textsuperscript{2} Alameda Applied Sciences Corporation, San Leandro, CA 94577, USA
\textsuperscript{3} LERMA, Université Pierre et Marie Curie, Observatoire de Paris and École Normale Supérieure, UMR 8112 CNRS, France
\textsuperscript{4} Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627-0171, USA
\textsuperscript{5}Present address: Sandia National Laboratories, Albuquerque, NM, USA

E-mail: f.suzuki@imperial.ac.uk

Abstract. Laboratory astrophysics is a novel approach to study different types of astrophysical phenomena by the means of carefully scaled laboratory experiments. Particularly, the formation of highly supersonic, radiatively cooled plasma jets for the study of protostellar jets is an active area of research at present. At Imperial College London, different experimental configurations allow producing plasma flows which are scalable to protostellar jets. The plasma is produced by introducing a \( \sim 1.4 \) MA, 250 ns current pulse from the MAGPIE generator into a load. By varying the geometry of the load it is possible to study different regions of interest in the jet. For instance, the effect of magnetic fields in the launching and collimation of the jet, and the propagation of the jet far away from the launching region as it interacts with the ambient medium. Two main experiments can address such regions of interest: radial wire arrays and radial foils. By using a radial wire array it is possible to produce a jet driven by a predominant toroidal magnetic field on the axis of a magnetic “bubble”, which expands with velocities up to \( \sim 300 \) km/s. In a radial foil the wires are replaced by a continuous disk allowing to produce a hydrodynamic jet, i.e. a jet in which magnetic fields are not dynamically significant. With this particular configuration it is possible to introduce a neutral gas above the foil in order to study jet-ambient interactions. Experimental results from different diagnostics will be presented together with 3-D MHD simulations using the GORGON code.

1. Introduction

Laboratory plasma astrophysics deals with the experimental modeling of astrophysical processes, including shock compression of materials under \( \sim \)Mbar pressures to study the equation of state of planetary interiors, laser-driven blast waves in atomic cluster media to study radiative cooling instabilities, and the formation/propagation of jets in regimes of interest to flows observed from newly forming stars. For a recent review of these and other applications see e.g. [1].
We are concerned with jets launched from young stars, known as Herbig-Haro objects, which play an essential role during star formation [2]. These are high Mach number flows whose dynamics are governed by magnetic fields and exhibit complex shock features from their interaction with the interstellar medium. In general these jets can be well approximated as ideal, magnetized, compressible plasmas, where viscosity, resistivity and thermal conduction are negligible (i.e. the dimensionless Reynolds, magnetic Reynolds, and Peclet numbers are $\gg 1$ respectively). The plasma flow can thus be described by ideal magnetohydrodynamics (MHD), with the same equations describing both the astrophysical jet and its laboratory counterpart [3, 4].

The investigation of jet formation mechanisms in young stars requires dynamically significant magnetic fields to be included. For jet propagation studies and jet-ambient interaction the jet can be considered as a hydrodynamic flow, as it is expected that far away from the launching source magnetic fields play a less important role in the dynamics of the jet.

![Figure 1](image)

**Figure 1.** (a) A radial wire array, (b) a radial foil.

2. Experimental setup
For studying magnetically-driven or hydrodynamic jets, the experimental arrangements are very similar, and are presented in figure 1 respectively. Their dynamics are presented schematically in figure 2. Two concentric electrodes drive a 1.4 MA, 250 ns current pulse from the MAGPIE generator [5] into a load, which depending on the experiment, will be made of discrete metallic wires (radial wire array) or a continuous metallic disk (radial foil). The current flows along the central electrode (with a typical diameter of 3–6 mm) and along the wires/foil, producing a toroidal magnetic field with a magnitude decreasing inversely proportional to the radius from the axis. As the current increases, the wires/foil are heated and converted into plasma, with the Lorentz force ablating plasma in a direction normal to their surface producing a background, low-density plasma. The ablation rate is maximum at the edge of the central electrode, where the magnetic field is the strongest. The absence of ablation above this electrode leads to ablated plasma from larger radii to converge on the axis due to radial pressure gradients, forming a plasma jet on the axis. The formation of this hydrodynamic jet is independent of the load, and continues until the end of the current pulse in radial foils (see figures 2(a)-(b)) [6, 7].

After the hydrodynamic jet is formed, radial wire arrays behave differently to radial foils. Radial wire arrays have less available mass for ablation in comparison to radial foils, and thus wires can reach full ablation near the central electrode, where the Lorentz force is the strongest. This leads to the formation of a radial gap, driving plasma above the initial position of the wires and forming a “magnetic cavity” (see figures 2(c)-(d)). Current can now flow along the plasma on the axis of the cavity and return along its walls, producing a toroidal magnetic field inside the cavity that confines and collimates a plasma jet. This marks the formation of a magnetically-driven jet [8, 9, 10].
3. Magnetically-driven jets from radial wire arrays
The dynamical evolution of a radial wire array consisting of 16 tungsten (13 μm diameter each) is presented from time-resolved (3 ns gate) XUV self-emission images of the plasma, presented in figure 3. The results were obtained from 2 nominally identical experiments. The early-time images show the formation of the magnetic cavity, which expands axially and radially. Typical expansion velocities are ∼100’s km/s, with the maximum axial velocity reaching ∼300 km/s. The formation of a jet on the axis of the cavity is observed at ∼200 ns. As the jet is compressed by the toroidal magnetic field, it is affected by current-driven instabilities. These instabilities lead the jet to detach from the base of the cavity at 240 ns, though it continues to propagate axially. The series of images from 358–386 ns used a larger field of view of the XUV cameras, allowing to follow the late-time evolution of the jet after detaching. It is seen that the jet becomes a series of highly-emitting clumps, which remain collimated as they propagate, indicating the possibility of trapped magnetic field in these plasma clumps. The presence of magnetic field in these clumps could also be an indication of high magnetic Reynolds numbers present in the plasma.

4. Hydrodynamic jet-ambient interaction in radial foils
The interaction of the jet with an ambient medium was achieved by injecting cold, neutral argon gas above the initial position of an aluminium foil (15 μm thick) using a solenoid-valve with a supersonic gas nozzle [11]. The tip of the nozzle was positioned 55 mm above the foil and 15 mm from the axis in order to prevent direct impact of the jet onto the nozzle. The valve was opened typically ∼350 μs before the start of the current pulse, with a duration of ∼200 μs. The nozzle released argon with a Mach number of ∼9 and a measured gas density at the position of the foil of ρ ∼3–5×10⁻³ kg/m³. Numerical simulations of the experiments were performed using the GORGON code [9], an explicit, parallel code designed to solve the resistive MHD equations on a three-dimensional Cartesian grid. The resolution of the computational grid was 200 μm.

The main features of a jet from a radial foil in vacuum and with the addition of argon are shown in figures 4(b)-(c) respectively. Both images were obtained at ∼430 ns using optical laser interferometry (λ=532 nm, ∼0.3 ns pulse duration) and represent 2-D maps of line-electron density, i.e. electron density integrated along the length of the plasma region. Without the presence of argon (figure 4(b)), the jet is a well defined, highly-collimated column with a typical diameter of ∼4 mm, and an aspect ratio (jet length to radius) >20. Abel inversion of these data results in typical electron densities in the jet of ∼10¹⁹ cm⁻³, surrounded by lower density plasma with a typical electron density of <10¹⁸ cm⁻³. Results from optical Thomson scattering show the jet is supersonic (Mach ∼3) and radiatively cooled, i.e. its cooling parameter <1.

The main features of the jet interacting with an argon ambient are presented in figure 4(c). A
jet with similar characteristics to the case in vacuum is observed, however the presence of argon leads to the formation of two prominent shock features. The first shock feature extends from the tip of the jet towards the edges of the foil in an “inverted cone” shape. The second shock feature is observed at this time ahead of the tip of the jet, forming a quasi-hemispherical shape and more resemblant to a bow-shock. The dynamics of the formation of these two shock features can be observed in detail in figure 5(a) from time-resolved images recording the self-emission of the plasma in the XUV ($h\nu > 30$ eV). These results allow measuring the axial tip velocities of both shock features, resulting in approximately constant axial velocities of $V_{jet} \sim 70$ km/s and $V_{bow} \sim 90$ km/s, i.e. the bow-shock moves faster by $\sim 30\%$.

Numerical simulations of the XUV emission are presented in figure 5(b), and show a very good agreement with the experimental data. The simulations indicate that the plasma flow from the jet and from the foil converge at the tip of the jet due to the presence of a radial component of the $J \times B$ force, i.e. some fraction of the current flows along the jet and along the inverted-conical shock. The convergence of current at the tip of the jet produces a compressing effect, which increases the density, temperature and pressure in this region, and explains the strong emission observed at the tip of the jet on the XUV images. The formation of the bow-shock ahead of the tip of the jet is due to the localized increase of pressure in this region, which creates strong axial pressure gradients, causing an acceleration of the plasma above it and producing a “nozzle-like” configuration. This allows plasma to propagate ahead of the tip of the jet at a higher velocity and interact with undisturbed argon.
5. Future work
The experiments presented here open new possibilities for the study of supersonic, radiatively-cooled plasma jets relevant to the physics of jets from young stars. Experiments using radial wire arrays allow producing a jet on the axis of a magnetic cavity, where a toroidal magnetic field is responsible for confining and driving the jet. This mechanism is similar to astrophysical scenarios where magnetic fields are responsible for the collimation of jets in young stars. The use of radial foils allows investigating the physics of the interaction of hydrodynamic jets, i.e. jets without a dynamically significant magnetic field, with the interstellar medium. The formation and interaction of the bow-shock ahead of the jet with the undisturbed argon ambient is very promising for the investigation of the effects of radiative cooling on the properties of forming working surfaces, which is highly relevant to astrophysical jets.
Acknowledgments
This work was supported by the EPSRC Grant No. EP/G001324/1, by the NNSA under DOE Cooperative Agreements No. DE-F03-02NA00057 and No. DE-SC-0001063, by DOE SBIR Grant DE-FG02-08ER85030, and by a Marie Curie European Reintegration grant.

References
[1] Remington B A, Drake R P and Ryutov D D 2006 Rev. Mod. Phys. 78 755-807
[2] Reipurth B and Bally J 2001 Ann. Rev. Astron. Astrophys. 39 403-55
[3] Ryutov D, Drake R P, Kane J, Liang E, Remington B A and Wood-Vasey W M 1999 ApJ 518 821-2
[4] Ryutov D D, Drake R P and Remington B A 2000 ApJS 127 465-8
[5] Mitchell I H, Bayley J M, Chittenden J P, Worley J F, Dangor A E, Haines M G and Choi P 1996 Rev. Scient. Inst. 67 1533-41
[6] Suzuki-Vidal F, Lebedev S V, Bland S N, Hall G N, Swadling G, Harvey-Thompson A J, Chittenden J P, Marocchino A, Ciardi A, Frank A, Blackman E G and Bott S C 2010 Phys. Plasmas 17 112708
[7] Gourdain P, Blesener I C, Greenly J B, Hammer D A, Knapp P F, Kusse B R and Schrafel P C 2010 Phys. Plasmas 17 012706
[8] Lebedev S V, Ciardi A, Ampleford D J, Bland S N, Bott S C, Chittenden J P, Hall G N, Rapley J, Jennings C A, Frank A, Blackman E G and Lery T 2005 Month. Not. R. Astron. Soc. 361 97–108 (Preprint arXiv:astro-ph/0505027)
[9] Ciardi A, Lebedev S V, Frank A, Blackman E G, Chittenden J P, Jennings C J, Ampleford D J, Bland S N, Bott S C, Rapley J, Hall G N, Suzuki-Vidal F A, Marocchino A, Lery T and Stehle C 2007 Phys. Plasmas 14 056501
[10] Suzuki-Vidal F, Lebedev S V, Bland S N, Hall G N, Harvey-Thompson A J, Chittenden J P, Marocchino A, Bott S C, Palmer J B A and Ciardi A 2010 IEEE Trans. Plasma Sci. 38 581-8
[11] Krishnan M, Wright J and Ma T 2009 AIP Conference Proceedings 1086 264–269 URL http://link.aip.org/link/?APC/1086/264/1