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"Re-creating the physics of astrophysical jets in laboratory experiments"

MAGPIE
Mega-Ampere Generator for Plasma Implosion Experiments

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MAGPIE project: http://dorland.pp.ph.ic.ac.uk/magpie/

This project aimed at studying the physics behind the formation of jets and outflows observed emerging from "protostars" (young stars in their formation phase), with a very unique approach: by reproducing their physics through scaled, laboratory experiments. This new research field is called Laboratory Plasma Astrophysics and it is based on the use of "plasma", a hot, ionised gas which makes up 99% of our visible Universe.

The new generation of space and ground-based observing facilities such as ALMA, the Atacama Large Millimeter Array in Chile, are beginning to deliver "first light" of these jets with unprecedented resolution. In addition the use of state of the art numerical codes is essential to benchmark experimental data in order to provide further insights into complex physical processes that are sometimes difficult to measure or interpret experimentally. In the same way, experiments provide the precise initial conditions to the codes for predicting the dynamical behaviour of the plasma. Laboratory Plasma Astrophysics aims at creating a strong synergy between observations, numerical simulations and experiments.

The work performed in the past 3 years has advanced our understanding of several aspects of astrophysical jets, focused particularly in the formation and dynamics of jets from young stars. These jets are characterised by being highly supersonic (Mach number>20), highly collimated, and showing the formation of spectacular radiative-shocks as the supersonic flow interacts with the interstellar medium.

Some of the key results of this project in the past 3 years were the following:

Magnetic fields as a mechanism to launch astrophysical jets

Most of the experiments were performed on the MAGPIE (Mega-Ampere Generator for Plasma Implosion Experiments) at Imperial College London, a device capable of producing an electrical current of 1.5 x 10^6 Amperes in a few 100's ns. This extremely large current very rapidly heats a metal (such as aluminium or tungsten) to convert it into plasma. The same current also generates a strong magnetic field that accelerates the plasma to produce supersonic flows with velocities >50 km/s. The geometry of the magnetic field in the experiments is similar to that of some astrophysical models of jet launching, namely the "magnetic tower" model, where a toroidal (azimuthal) magnetic field confines and collimates plasma on the axis of a magnetic "bubble". This astrophysical model can be studied in MAGPIE by introducing the electrical current into a metallic disc or "radial foil Z-pinch" [1]. The experiments are characterised by the formation of several magnetic bubbles (4-5 episodes per shot), as shown in Fig. 1. The data show the jet evolves into an unstable plasma column due to the formation of instabilities driven by the toroidal magnetic field confining the jet. The data also show that remnants of the first ejections tend to improve the length and collimation of the jet during each subsequent episode. This is consistent with observations of stellar jets characterised by the appearance of periodic features along the jet or "knots". However it is not known at present whether these features are formed due to episodic ejections from the source, or the formation of plasma instabilities of an initially smooth supersonic flow. Thus this new experimental platform might provide new clues on the formation of stellar jets and their connection with magnetic fields.

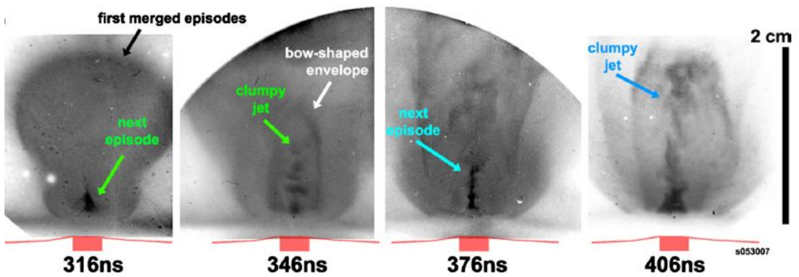

Figure 1: Episodic magnetic bubbles produced on MAGPIE [1].

Shock formation from jet-ambient interaction

Stellar jets are characterised by spectacular, terminal bow-shocks due to the interaction of the supersonic jet with the interstellar medium. Thanks to observations with the Hubble Space Telescope spanning more than 10 years [2], it is now possible to follow the trajectories and record the dynamical changes of many features present in these objects. An example of observations of the jet HH47 is shown in Fig. 2a. During my project, I have created an experimental platform to mimic such dynamics by producing a stable, supersonic jet using an aluminium radial foil [3]. In order to study jet-ambient interactions in the laboratory, a neutral gas (e.g. Argon) was injected above the foil using an electromagnetic valve with a supersonic nozzle. This allowed control of ambient properties such as the gas composition and density. Typical results are shown in Fig. 2b and are characterised by the formation of a quasi-spherical shock which expands with an axial velocity of ~100 km/s. The results also show the formation of spatial features (typical size~200 μm) on the shock front, which are consistent with strong effects of "radiative cooling", i.e. photons emitted from the shock which modify the gas ambient ahead of it, a predominant process in jets from young stars. The experimental results were benchmarked with the 3-dimensional, Magneto-Hydrodynamics (MHD) numerical code Gorgon (Fig. 2c), showing a good agreement with the data allowing to obtain, for instance jet and shock dynamics. Future work will aim at studying the effect of different ambient parameters, such as gas composition and distribution, to study for instance the formation of shocks in a stratified ambient medium.

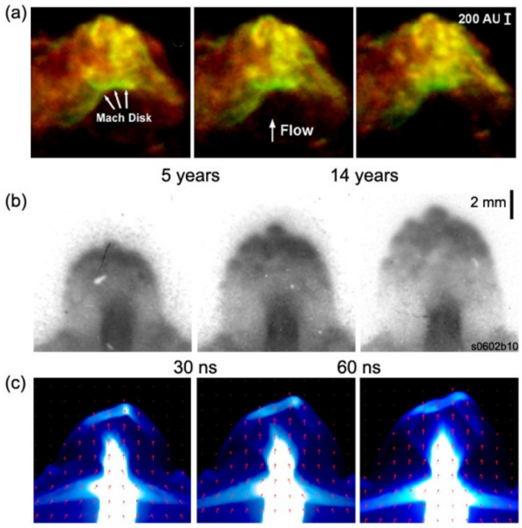

Figure 2: (a) Observations of bow-shocks from stellar jets. (b) Experimental results of shock formation in Argon on MAGPIE. (c) Numerical simulations using the MHD code Gorgon.

Measuring jet parameters with new laser diagnostics

One of the main goals of this project was to implement novel diagnostics to measure the conditions of plasmas produced on MAGPIE, for instance jet temperature, velocity and density. This was achieved with CERBERUS, a multi-beam, high-power laser system (1 TW power) developed by the Quantum Optics and Laser Science Group. This laser was used to perform "Thomson scattering", a technique which consists on focusing an 8 J, 8 ns duration laser pulse into the plasma. The spectrum of light dispersed from the plasma from different directions contains information of plasma properties such as temperature and velocity. Results of jets from radial foils show the plasma jet propagates at velocities of ~50-60 km/s, with a temperature of ~20 eV, consistent with numerical simulations of the experiments using Gorgon.

Another diagnostic technique based on the use of lasers is "optical interferometry", where a low-energy (200 mJ), ~1 ns duration laser is used to take an instantaneous image of the plasma. This diagnostic provides 2-dimensional maps of integrated electron density along the plasma. However, the high degree of azimuthal symmetry of the experimental jets make possible to extract the radial distribution of electron density using "Abel inversion". During this project I worked in collaboration with PhD students of the Plasma Physics Group to develop and refine the analysis of results from plasma jet experiments in MAGPIE, resulting on the code "MAGIC". This tool is not useful only for plasma jet experiments, but also for other experimental applications that use the same diagnostic technique.

References

[1] F. Suzuki-Vidal, et al., "Generation of episodic magnetically driven plasma jets in a radial foil Z-pinch," *Physics of Plasmas*, vol. 17, no. 11, p. 112708, 2010.

[2] P. Hartigan, et al., "Fluid Dynamics of Stellar Jets in Real Time: Third Epoch Hubble Space Telescope Images of Hh 1, Hh 34, and Hh 47," *The Astrophysical Journal*, vol. 736, no. 1, p. 29, Jul. 2011.

[3] F. Suzuki-Vidal, et al., "Interaction of a supersonic, radiatively cooled plasma jet with an ambient medium," *Physics of Plasmas*, vol. 19, no. 2, p. 022708, 2012.